FINAL REPORT

Title: Landscape Evaluations and Prescriptions for Post-Fire Landscapes

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Abbreviations

CNF—Colville National Forest
DAP—Digital aerial photogrammetry
LiDAR—Light detection and ranging
OWNF—Okanogan-Wenatchee National Forest
GNN—Gradient nearest neighbor
HRV—Historical range of variability
FRV—Future range of variability
PI—Photo-interpreter
GIS—Geographic Information System
PCA—Principal Components Analysis

Keywords

Fire effects, fire ecology, salvage logging, post-fire management, landscape evaluations, surface fuel, canopy fuel, forest structure, landscape pattern, spatial pattern, reburn, Colville National Forest, Okanogan-Wenatchee National Forest

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Abstract

Wildfires are modifying the structure and composition of forests at rates that far exceed mechanical thinning and prescribed fire treatments. We responded to this by analyzing recent wildfires to understand drivers of fire-severity and post-fire vegetation development, with an emphasis on how pre- and post-fire management and prior disturbance history modulate these responses, and by evaluating the degree to which fire reduced landscape departure and restored fire-prone forest landscapes. We used field and remote sensing methods to investigate these topics, with forests of northeastern Washington, USA as a model system for our work.

There was abundant post-fire tree regeneration one to three decades after fire, with little evidence of recruitment failure. We found an influence of both average climate and post-fire weather, with higher seedling densities associated with cooler and moister conditions. This weather and climate signal portends potential recruitment limitation following future fires that occur in warmer and drier conditions. Post-fire harvest had a simplifying effect on residual forest structure relative to paired controls, but the effect of fire severity was stronger than that of post-fire treatments. Post-wildfire prescribed fire applied in areas that burned at lower severity further decoupled surface and canopy fuels, promoting fire-resistant open canopy structure. Daily weather and annual climate anomalies had the strongest influence on burn severity, but recent prior vegetation management, and especially prior prescribed fire and wildfire, moderated burn severity. Large, unplanned wildfires caused variable and contrasting outcomes—they rapidly reorganized the vegetation mosaic in ways that planned vegetation treatments do not. In some areas, fires made progress towards restoration and climate adaption goals, improving alignment of the forest structural mosaic with HRV-FRV envelopes and reestablishing stabilizing fire-vegetation feedbacks. However, wildfires sometimes increased departures from HRV-FRV benchmarks, for example by creating vast open patches, reducing or eliminating large-tree dominated patches, or causing transitions to uncharacteristically large non-forest patches.

Post-fire landscape management principles synthesized from our work include:

- Protect fire refugia and legacy large diameter trees.
- Use places where fire reinitiated or strengthened stabilizing feedbacks as core areas from which to grow forest landscape resilience.
- Differentiate irreversible conversions to non-forest due to climate-limited tree establishment from reversible transitions due to dispersal limitation.
- Align species composition and structure with future fire regimes and climate.

We illustrate application of these principles using the landscape prescription concept in a geospatial framework. An important theme is a shift away from a post-fire management paradigm focused on economic salvage harvest in individual easily accessed stands that burned with high severity, with little regard for overall landscape pattern or context. Our post-fire management principles help align overall landscape pattern with HRV-FRV benchmarks that promote resilience and adaptation to future climate and fire regimes, using a variety of post-fire treatments, such as planting climate-adapted species in dispersal limited areas, and green tree thinning, "salvage from below," and post-wildfire prescribed fire in places that burned at lower severity.

Objectives

Wildfires across the western US are modifying the structure and composition of forests at rates that far exceed mechanical thinning and prescribed fire treatments (Valliant and Reinhardt 2017). Thus, credible stewardship of western forests must consider the effects of recent and future wildfires in a whole-landscape framework. The need to modify forest structure and composition across large portions of fire-prone forests to increase resistance and resilience to fire and climate change is well established (Churchill et al. 2013, Hessburg et al. 2015), and evidence of the potential effectiveness of such treatments continues to accumulate (Prichard et al. 2014, 2020). Although the pace and scale of active management efforts have been increasing, the reality is that wildfire is, and will continue to be, the primary agent affecting vegetation and fuels across forests of the West for the foreseeable future (Higuera and Abatzaglou 2020). This underscores the need to deliberately build the occurrence and effects of recent and future wildfires into landscape analysis and planning.

We responded to this need by analyzing recent wildfires to understand drivers of fire-severity and post-fire vegetation development, with an emphasis on how pre- and post-fire management and prior disturbance history modulate these responses, and to evaluate the degree to which fire reduced landscape departure and achieved fire-prone forest restoration targets. We synthesize our results in a post-fire landscape management framework using the landscape prescription concept (Hessburg et al. 2015). The forests of north central and northeast Washington State serve as a model system.

Our project objectives were to:

Objective 1: Investigate what factors influence the recovery and development of vegetation structure after fires, including post-fire management activities vs. no post-fire management.

Objective 2: Determine what factors explain fire severity of all fires since 1984 across the whole study area. In particular, assess how post-fire management actions affected subsequent re-burns. Develop a predictive, geospatial model from this analysis to predict probabilities of future fire severity.

Objective 3: Assess how prior fires and especially the large fires in 2014 and 2015 affected landscape level structure, composition and pattern of vegetation and fuels relative to Historical and Future Range of Variation envelopes (HRV and FRV) in 3-4 subwatersheds (HUC 12).

Objective 4: Work with managers to create a post-fire "landscape prescription" for the 3-4 sub-watersheds from Objective 3 that move watersheds towards alignment with HRV and FRV envelopes.

Objective 5: Evaluate how different data sources and reference condition datasets affect our ability to assess landscapes, evaluate departure, and develop post-fire management prescriptions.

Objective 6: Initiate and foster science-based discussion and decision making about wildfires and post-fire management among managers and collaborative stakeholders.

Background

Despite the large and increasing number of acres burned by wildfires each year, managers lack tools and workflows to evaluate how fires are shaping landscape patterns relative to reference conditions and management objectives to promote landscape resilience. The scientific basis for treatments to restore forest structure and enhance resilience in fire-excluded and long-unburned forests is very mature (Stephens et al. 2020), and the application of this knowledge to guide management actions is similarly sophisticated (WADNR 2020). However, analysis and management of recently burned landscapes lags behind that of unburned landscapes in both theory and in practice. Post-fire landscape management currently focuses on short-term emergency mitigation measures (Robichaud et al. 2009), economic salvage logging (Nemens et al. 2015), and planting (North et al. 2019). Consequently, managers presently lack a framework to guide prioritization of post-fire management actions in an integrated landscape framework. Without a clear scientific basis for why and where treatments are needed to restore or enhance ecological function, resilience, and climate change adaptation, discussions of post-fire management often become embroiled in controversy around a single management action, economic salvage logging (Nemens et al. 2015, Powell 2019).

Wildfires result in a much wider range of effects than are typically caused by planned vegetation treatments. In some areas wildfires burn with characteristic severity and function to maintain resilient conditions by reducing fuels and restoring stabilizing feedbacks (Larson et al. 2013), restore forest structural patch mosaics (Belote et al. 2015, Berkey et al. 2020), and create opportunities for ecosystem alignment to changing climate through tree regeneration (Povak et al. 2020). However, wildfires can also cause extreme changes that fragment or eliminate patches with large trees and dense canopy, thereby reduce habitat for species of concern (Schwartz et al. 2013, Vanbianchi et al. 2017). Wildfires are also accelerating transitions to non-forest with growing evidence of conifer tree recruitment failure and transition to persistent, climate-enabled transition to non-forest (Davis et al. 2019, Kemp et al. 2019), and type conversion to non-forest due to dispersal limitation and vegetation-fire regime positive feedbacks (Coop et al. 2020). Thus, wildfires present both opportunities and challenges to which land managers and decision makers must respond with post-fire management.

Study Area and Report Organization

The study area comprises the forested regions of north central and northeastern Washington, USA. We used fire history records from forested areas of all land ownerships in our fire severity (Objective 2) analysis; our field plots (Objective 1) and focal burned watersheds (Objectives 3, 4 & 5) were located on US Forest Service lands on the northern portion of the Okanagan-Wenatchee National Forest and the western half of the Colville National Forest.

We organize the central body of this report (Methods, Results and Discussion) by individual objective or groups of closely related objectives because they each have different research questions, data sources, response variables, and analytical methods. This format allows for more coherent presentation of different analyses and findings. We report science delivery activities and overall conclusions for the entire project in stand-alone sections.

Objective 1: Development of Vegetation Structure after Fires, Including Post-Fire Management

Research questions and study design

We addressed this objective through two studies: a field-based investigation of post-fire tree regeneration (Povak et al. 2020), and a LiDAR-based analysis of forest structure. In both cases, we sought to evaluate the effects of post-fire vegetation management on forest development.

Post-fire tree regeneration

We asked if conifer tree regeneration depended on fire severity, post-fire salvage logging (without post-harvest planting), potential vegetation type (PVT, dry mixed-conifer, moist mixed-conifer, or cold dry-forest). To understand the climatic context of post-fire tree regeneration, we assess short-term (1 to 3 year) post-fire weather and placed our results within a broader context of postfire regeneration studies conducted in the western US.

Post-fire forest structure

We asked if forest structure, as measured by airborne LiDAR, differed between burned areas that received post-fire treatments from areas with similar bioclimatic environments and fire severity that were not treated following fire. We considered the four most common post-fire treatments across our study area: harvest, harvest and planting, planting alone, and prescribed fire.

Methods

Post-fire tree regeneration

The selection of potential field plots proceeded as follows: a 30-m grid of points was overlaid across the northern half of the ONF and eastern half of the CNF within a geographical information system (GIS). Sample sites were retained if they satisfied 6 criteria: they were (1) within a fire perimeter that occurred prior to 2007, (2) >30-m inside a fire severity patch of moderate or higher severity, (3) within a dry-mixed, moist-mixed, or cold-dry conifer type, (4) within an area of recent LiDAR acquisition, (5) within 3-km of a road, and (6) suitable for sampling after evaluation with aerial photography.

Our selection protocol resulted in a universe of 166,822 potential sample plots. We used a stratified random sampling design to create a complete matrix of the 12 experimental strata. Twenty-five sample plots within 12 bins were randomly located across NF lands, for a total of 300 target sample locations to complete the 3 (PVT) x 2 (severity) x 2 (salvage) study design. Field implementation of this protocol resulted in 248 plots in the final frame; of these, 146 were located on the CNF, and 102 on the ONF (Fig. 1). Final sample plots were located within fires that burned in 1988, 1994, 2001, and 2003.

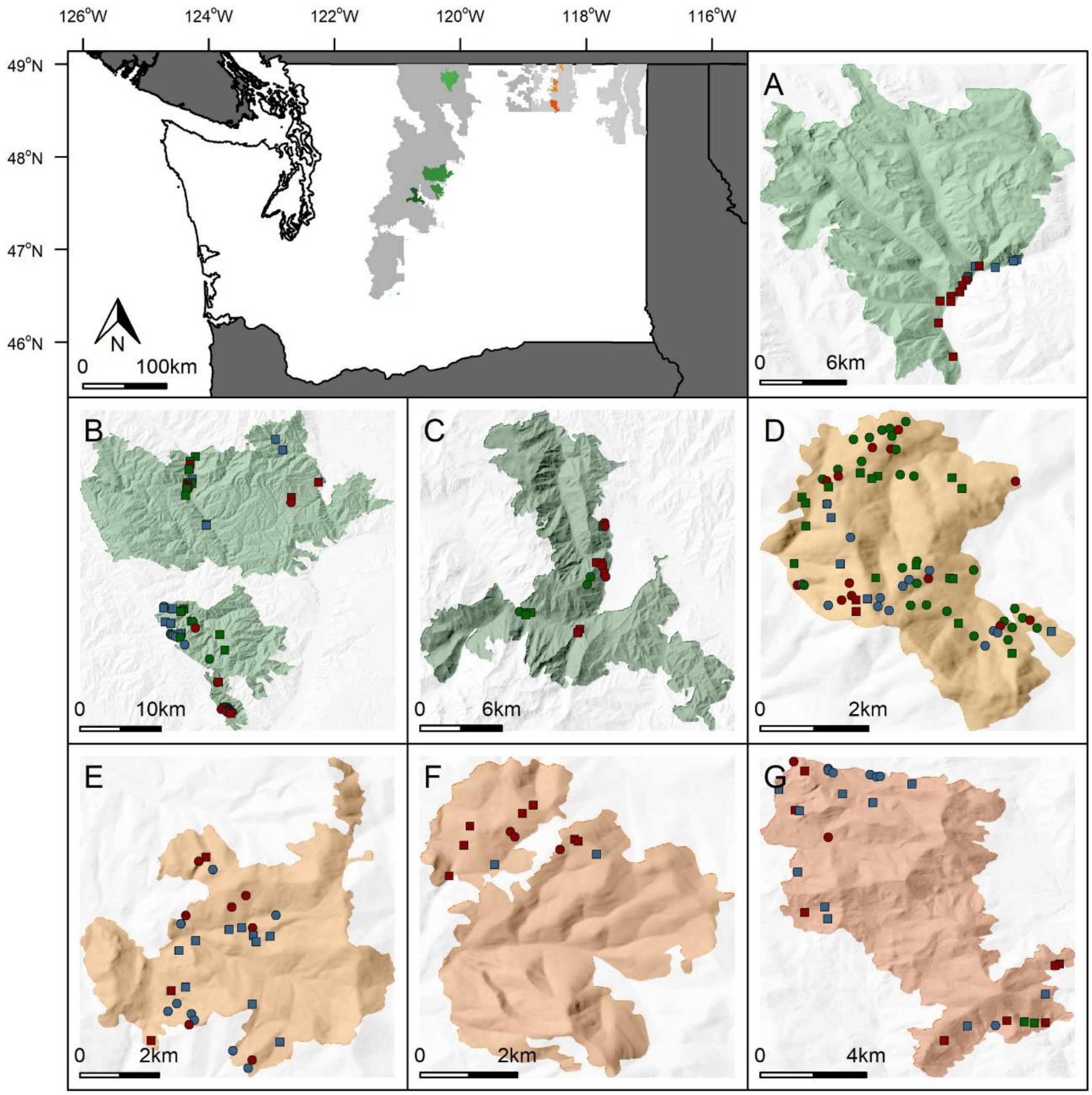

Figure 1. Study proximity map, fire perimeters and plot locations within the Okanogan-Wenatchee (dark gray, green shaded fires) and Colville National Forests (light gray, orange shaded fires) in central Washington State. Study plot colors indicate forest type (red, dry forest; green, moist forest; blue, cold forest). Plot shapes indicate postfire management applied (squares, salvage harvest; circles, no management).

We recorded measurements of overstory trees and tallied young trees and non-tree vegetation cover within sampled plots. A fixed 16-m radius circular plots was spatially referenced at plot center using a high accuracy GPS unit (Javad Triumph 2 GNSS receivers collecting GPS and GLONASS L1 and L2 data). Global positioning data were collected for 15 to 30 minutes, in one-second epochs. These data were later post-processed using Javad Justin software (V2.122.160.95). Within the 16-m plot, four subplots were established at cardinal directions, where tree regeneration (stems < 4-m height) was tallied by species and height class (<1-m, 1 to 2-m, 2 to 4-m heights). Plots varied in size depending on a prior assessment of regeneration density. Where regeneration density was high, plot sizes were reduced to reduce survey time. Subplots varied in size from 16 x 0.5-m (0.0008 ha; n = 36), 16 x 2-m (0.0032 ha; n = 120) to the full 16-m circle (0.08 ha; n = 92).

We used a mixed-effect generalized additive modeling (GAM) approach to identify 1) significance among experimental design factors (fire severity, salvage/no salvage, and PVT) while accounting for 2) significant environmental covariates of regeneration density, 3) potential interactions between environmental cofactors and NF membership, and 4) a random effect of plot membership within individual fires. The use of GAM over generalized linear models allowed for the use of smoothing splines to account for nonlinearities between regeneration density and other model covariates. GAM models were first run with the full set of 1) experimental design factors (fire severity class, PVT, salvage/non-salvage, and NF membership), 2) then with a restricted set of nine environmental cofactors, and 3) with a random effect for fire membership.

Post-fire forest structure

We used airborne LiDAR to quantify canopy height, canopy cover, canopy complexity, and the relative distribution of canopy cover among different height strata. LiDAR data with high density of point returns can also be used for individual tree detection (ITD), by grouping the raw lidar point cloud into objects based on the locations of point returns in proximity to each other (Breidenbach et al. 2010). Identification of all individual trees is difficult when canopies overlap, but identification of dominant overstory trees can be achieved with high fidelity (Jeronimo et al. 2018). We refer to dominant overstory trees identified through IDT methods as tree-approximate objects (TAOs) (North et al. 2017), in in an effort to distinguish them from true individual trees. Using TAOs allows us to quantify the patterns of individual trees, following methods from Individuals, Clumps, and Openings (ICO) methods described by Churchill et al. (Churchill et al. 2013). When applied to Lidar data, the ICO method can be quantified by the percent of canopy area in TAO clumps of different sizes (Jeronimo et al. 2018), in contrast to field-based methods that use the percent of trees in tree clumps of different sizes (Churchill et al. 2013).

LiDAR data for this project came from n=11 flights that occurred between 2012 and 2018. All LiDAR flights were of sufficient quality to allow for the calculation of "gridmetrics" in the program FUSION (McGaughey 2018). Gridmetrics statistically summarize the LiDAR point returns (Table 1), producing a 30-m resolution raster layer of forest structure metrics. All but one of flights contained high enough pulse densities to also calculate a canopy surface model, needed for additional forest structure metrics, including canopy cover within different vertical strata, and to identify TAOs. When LiDAR flight data overlapped, we used the most recent LiDAR acquisitions, since we are interested in long-term structural changes after fire. The exception was for the "Colville 2012" acquisition, which was flown at a lower point density and therefore could only be used for standard gridmetrics data, which we prioritized last. Lidar Gridmetrics, Canopy area metrics, and Lidar-based measurements of Individuals, Clumps, and Openings (hereafter "LICO metric") are summarized in Table 1.

Fire perimeters from the US National Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al. 2007), WA DNR, and United States Forest Service (USFS) were used to identify areas that had burned between 1984-2016, in fires ≥121 ha in size. Burn severity was mapped using the Relative difference Normalized Burn Severity Ratio (RdNBR; Miller and Thode 2007; Miller et al. 2009), which provides a relative accurate measurement of changes on the ground due to fire in northeastern Washington (Cansler and McKenzie 2012). We calculated RdNBR in Google Earth Engine, using composites of pre-fire and post-fire images, following the methods of (Parks et al. 2018). We modified those methods to shift the image dates to start later, from June 15 - September 15, better matching the snow-free period in northern Washington. The unclassified RdNBR was then smoothed with a 3x3 smoother, to reduce pixel registration errors. We excluded any areas that had burned two or more times between 1984 and 2016 from the dataset. We also exclude any areas that were treated before fire from treatment and control datasets. We overlaid the available LIDAR data with the burn severity atlas, which provided us with samples from treated and untreated areas from 61 fires.

We compared post-fire treatments—including salvage, thinning, and planting—to burned areas with similar bioclimatic environments and fire severity. We matched each treatment observation with a control observation using the following criteria: (1) within the same LIDAR acquisition, and (2) the first try that that was +/- 10% of both AET, CWD, and RdNBR. If no match was found, then we did not include that sample in the analysis. Sampling was without replacement; a control point was used only once. We retained information on AET, CWD, fire severity, and time since fire (between fire and LIDAR acquisition) for each sampled pixel and plotted these response variables to confirm that the samples were well matched. To compare treatment and control distributions we test for statistical differences in means between the control and each treatment a K-S test, and plot density distributions for each treatment + control combination.

Table 1. Lidar-based forest structure metrics use to quantify vertical, horizontal, and tree clumping patterns in this study.

Forest structure attribute	Abbreviation
Gridmetrics (30 m window) & cloud metrics (circular plot of given radius)	
Dominant canopy height	Elev p95
Canopy complexity	Elev stddev
Cover above 2 meters	CanCov
Canopy area (90 m window) & cloud metrics (circular plot of given radius)	
Percent of canopy area in 2-8 m stratum	CA 2to8
Percent of canopy area in 8-16 m stratum	CA 8to16
Percent of canopy area in 16-32 m stratum	CA 16to32
Tree Approximate Object **Lidar Individual Clumps and Openings (LICO) (90m window):**	
Percent of canopy in clumps of 1 tree	1Tree
Percent of canopy in clumps of 2-4 trees	2-4 trees
Percent of canopy in clumps of 5-9 tree	5-9 trees

Results and Discussion

Post-fire tree regeneration

Regeneration was abundant across the entire study area (Fig. 2). Median regeneration density across the 248 sampled plots was 4,414 stems · ha^{-1}, with lower, upper quartile values of [733, 20,352], respectively (Fig. 3). Only four plots (1.6%) had no regeneration present, 17 plots (6.9%) had <100 stems · ha^{-1}, and 37 (15%) had <350 stems · ha^{-1}; the latter of which represents a minimum acceptable stocking level by the Washington State Department of Natural Resources, which is similar to minimum stocking standards on NF lands. When only large conifer regeneration was considered (2 to 4-m height), median density was 687 stems · ha^{-1} (IQR: 3,919 stems · ha^{-1}), and only 24 plots (9.7%) recorded no large conifer regeneration.

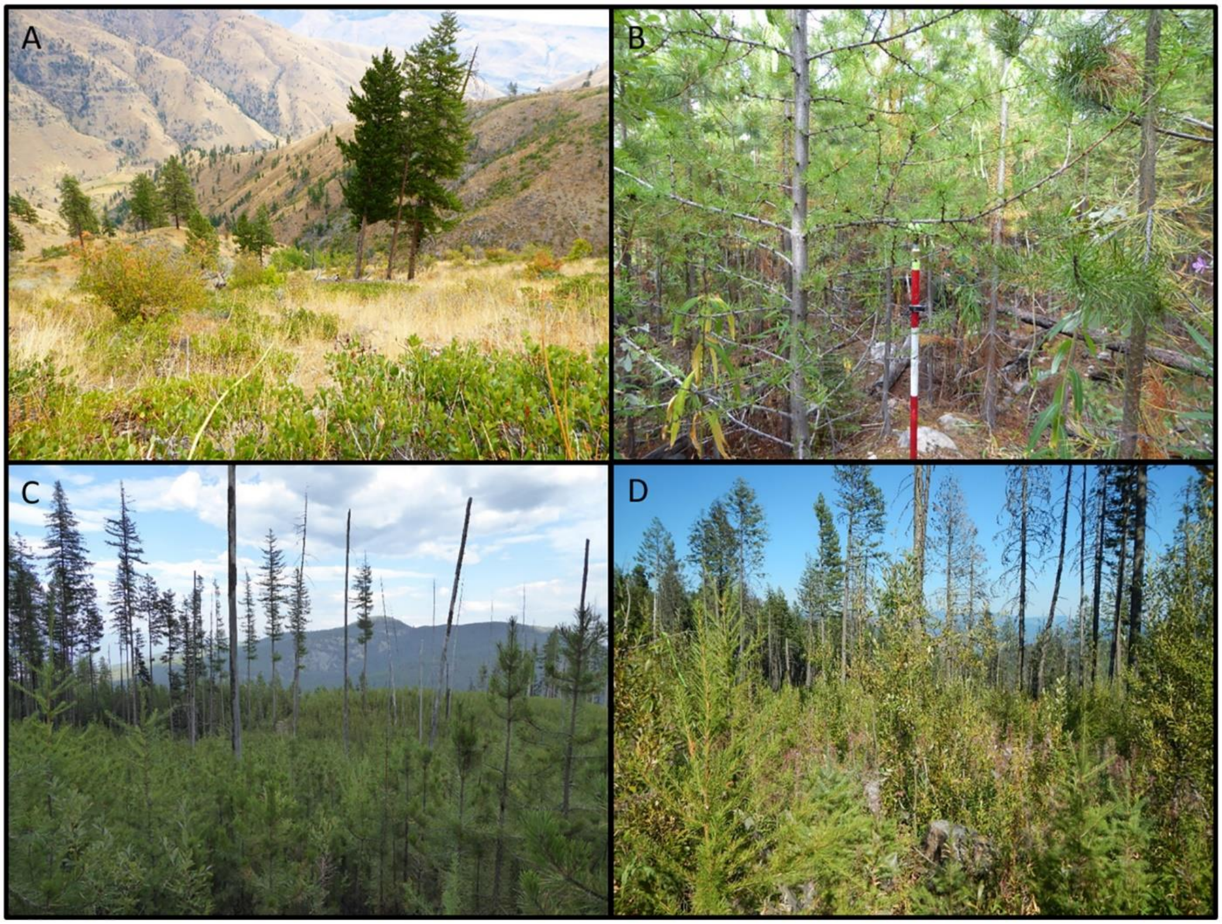

Figure 2. Plot photos from A) a moderate-severity fire in dry mixed-conifer forest with salvage harvesting, B) a high-severity fire in moist mixed-conifer forest with no postfire management, C) a high-severity fire in a cold dry forest with salvage harvesting, and D) a moderate-severity fire in moist mixed-conifer forest with salvage harvesting.

Douglas-fir was the dominant regenerating species, representing 37% of stems across all size classes. Lodgepole pine and ponderosa pine each comprised ~15% of the regeneration, and Engelmann spruce and western larch represented ~10%. Douglas-fir was present on >94% of plots with a median density of 1,367 stems · ha^{-1}, when present. Ponderosa pine and Engelmann spruce were present on 40% of plots, and had median densities of 243 and 1,250 stems · ha^{-1} where present, respectively. Similarly, lodgepole pine and western larch occupied ~50% of plots at median densities of 634 and 2,031 stems · ha^{-1} where present, respectively.

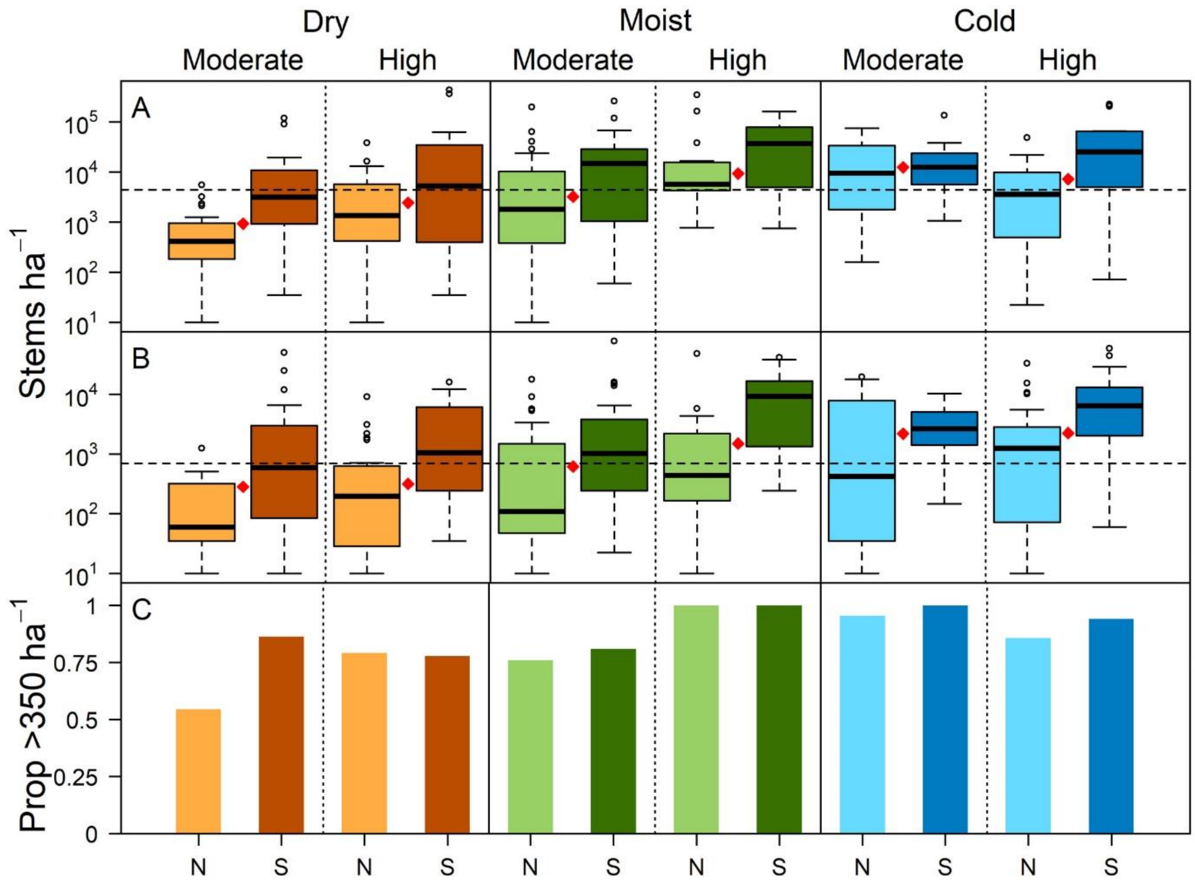

Figure 3. Boxplots depicting postfire tree regeneration density by management treatment, burn severity and forest type for (A) all regenerating stems, (B) tall conifer (2-4m height) stems, and (C) barplots showing the proportion of plots within each sample stratum with >350 stems · ha-1. Acronyms are: N- no salvage treatment, and S-salvage harvested. Dashed horizontal lines in A and B represent median densities across all plots. Box-and-whisker plots were constructed using the default boxplot function in the R graphics package, and boxes represent the 25th, 50th, and 75th percentiles. Whiskers extend to the most extreme data point no further than (1.5 * IQR) + 75th percentile or (1.5 * IQR) – 25th percentile, and points represent data outside those ranges. Red diamonds in boxplots indicate median densities for the respective forest type and burn severity class summarized across management treatments. Moderate and high refer to fire severity.

The main effect of postfire salvage was significant (F = 11.05, P = 0.001) (Fig. 3). Mean regeneration densities were 2.5-times greater on salvaged versus non-salvaged plots. A significant interaction was found between salvage treatments and NF land status (F = 13.11, P=0.000). On the CNF, mean density on salvage plots was 51,859 stems · ha^{-1} compared to 21,095 stems · ha^{-1} for non-salvaged plots. On the ONF, mean density was greater on non-salvaged plots, 6,747 stems · ha^{-1} vs, 2,574 stems · ha^{-1} salvaged). Similar trends were found for large conifer regeneration (Fig. 3).

Regeneration density was highest on salvaged plots for all species except ponderosa pine, and the main effect of salvage was significant large conifer (F = 37.87, P = <0.001) and Engelmann spruce (F = 4.78, P = 0.030) regeneration. Mean spruce density was more than twice as abundant on salvaged (5,037 stems · ha^{-1}) vs non-salvaged (2,314 stems · ha^{-1}) plots. Douglas-fir exhibited a significant interaction between salvage and NF status (F = 6.00, P = 0.015), where only small differences in regeneration density were observed on the ONF, but on the CNF, density increased nearly 2-fold after salvage harvesting. A similar result was identified for all species combined. Overall, species composition was similar for salvaged and non-salvaged plots.

Post-fire (1 to 3 yr) weather conditions were generally cooler and wetter than the 1965-2016 average across the sampled fire locations (Fig. 4). Median MAT was below the 50^{th} percentile and median MAP was at the 72^{nd} percentile. Only one-third of plots experienced MAP below the 50^{th} percentile. Median moisture deficit was at the 22^{nd} percentile, with a few outlier plots experiencing deficits above the 50^{th} percentile (Fig. 4). A negative relationship was found between postfire percentile temperature and years since fire (r = -0.961; Fig. 8), indicating that postfire MAT increased over time such that warmer conditions were experienced in more recent fires compared to older fires.

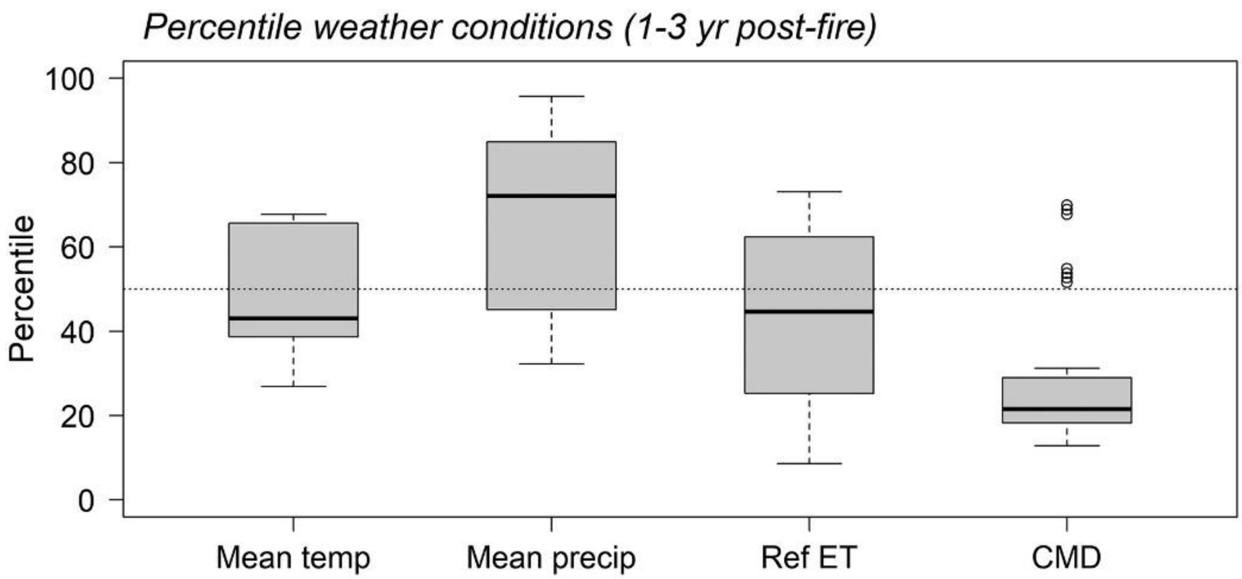

Figure 4. Mean percentile postfire (1-3 yr) weather conditions for sampled points (n = 248). Ref ET is reference evapotranspiration and CMD is climatic moisture deficit.

Postfire weather variables were significant drivers of regeneration density, and percentile conditions were generally cooler and moister in the 1- to 3-year period after the fires than for the >50-year climate record (Fig. 4). The regeneration response to postfire temperatures (i.e., 3-year mean temperatures) varied across NFs, with a positive relationship on the CNF and a negative or neutral relationship on the ONF. Increases in postfire precipitation led to increased regeneration density on both NFs for all species combined, large conifer, and Douglas-fir regeneration, and no other significant trends were identified. Trends were not significant for ponderosa pine for either postfire temperature or precipitation.

The great majority of plots measured in this study are on a successional trajectory towards an overly dense forest condition. Little evidence of complete regeneration failure was apparent for the postfire landscapes of our study area, suggesting that non-forest vegetation did not significantly inhibit tree regeneration, establishment, or growth across the sampled environmental gradients. However, the applicability of our results to future fires is less clear. We found that postfire weather in our study was favorable for tree regeneration for the fires we studied. In contrast, postfire weather for more recent fires has much hotter and drier compared to the previous 30 years, and the prospects of warmer and drier future conditions are clear. In a recent detailed assessment of the climatic drivers of postfire regeneration across much of the western US, Davis et al. (2019) found that certain seasonal and annual climate variables have recently crossed key physiological tolerances relevant to successful Douglas-fir and ponderosa pine regeneration. The authors suggested that future climate change may lead to ecosystem transitions to non-forest types in some affected forests.

Our results suggest that successful regeneration for different coniferous species will be contingent upon synchrony between sufficient seed crops from mature surviving trees, and a favorable 2-5 year period when temperature and precipitation levels are moderate and within seedling tolerances. However, this does not preclude subsequent drought-induced die-off events. While climate projections indicate an overall trend towards warmer and drier conditions, there will still likely be periods of more favorable climate for tree regeneration due to multi-annual climatic oscillations in ENSO and the PDO. However, seed dispersal limitations will likely increase as the size and severity of fires continue to increase, particularly for species that are primarily wind dispersed. Planting may be used to foster the development of these species within burned areas, where long distances to mature canopy trees exists (North et al. 2019), and where projected MAT and MAP conditions are deemed suitable to successful tree regeneration and ongoing forest development. However, in areas that are less than suitable for conifer establishment, managers might consider avoiding replanting and allowing a smooth transition to nonforest conditions. Likewise, where MAT and MAP suggest changes in site suitability for certain conifers, managers might also consider assisting in these transitions by replanting species that will be better adapted to the shifting conditions (North et al. 2019, Stevens-Rumann et al. 2019, Stevens-Rumann and Morgan 2016).

Post-fire forest structure

The different post-fire treatments occupied different regions of fire severity and climate space (Fig. 5), underscoring the necessity of the matched case-control sampling design to evaluate treatment effects on forest structure. Post-fire harvest was distributed across a broad range of climate space and tended to have lower burn severity than sites treated with combined harvest and planting or planting alone (Fig. 5). Sites where planting was used—with or without harvest—tended to have similarly high burn severities but differed strikingly in climate. Sites that were treated with combined harvest and planting occurred in productive (high AET) and low drought stress (low Deficit) locations, while areas treated with post-fire planting alone were in low productivity, high drought stress locations. Sites treated with post-fire prescribed fire had intermediate fire severity, productivity, and drought stress.

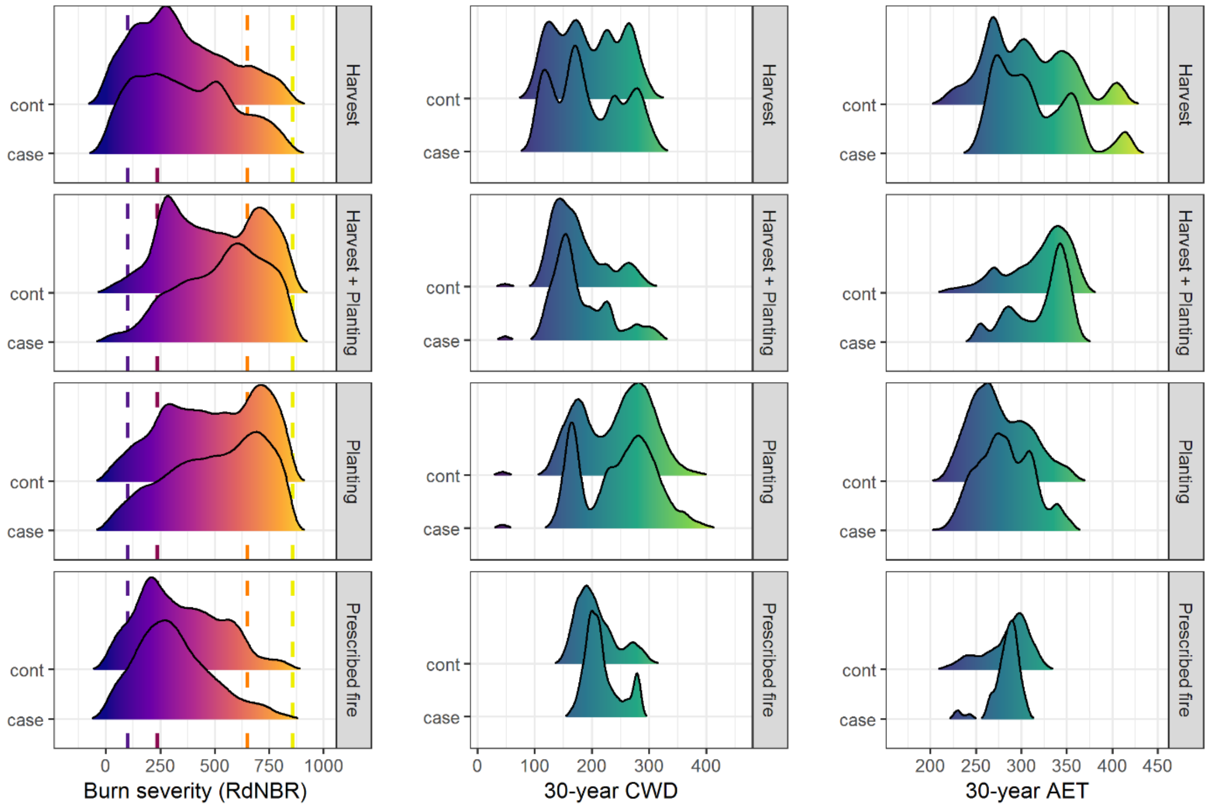

Figure 5. The distribution of different post-fire treatments in fire severity (left panels), climatic water deficit (center panels) and actual evapotranspiration (right panels) space. CWD is a measure of drought stress (higher values = greater drought stress) and AET is a proxy for potential productivity (higher values = greater potential productivity).

Table 2. Kolmogorov-Smirnov test results for LiDAR-derived canopy structure metrics. Tests evaluate differences between the case and control distributions in each panel of the left three columns in Figure 6.

Treatment	Metric	*D*	*P*-value
Harvest	dominant canopy height	0.143	<0.001
	canopy complexity (elevation S.D.)	0.169	<0.001
	total canopy cover (%) > 2 m	0.080	<0.001
Harvest + Planting	dominant canopy height	0.297	<0.001
	canopy complexity (elevation S.D.)	0.322	<0.001
	total canopy cover (%) > 2 m	0.196	<0.001
Planting	dominant canopy height	0.168	<0.001
	canopy complexity (elevation S.D.)	0.170	<0.001
	total canopy cover (%) > 2 m	0.113	<0.001
Prescribed fire	dominant canopy height	0.058	<0.001
	canopy complexity (elevation S.D.)	0.047	0.004
	Total canopy cover (%) > 2 m	0.112	<0.001

Post-fire treatments showed statically significant, but generally small magnitude, differences between untreated burned controls (Table 2). The effect of harvest alone or harvest combined with planting was to simplify residual forest canopy structure relative to paired untreated controls (Fig. 6). This is evident in more frequent low values for dominant tree heights and canopy complexity, and generally lower proportional distribution of canopy cover in taller height strata in the treated sites compared to the paired untreated controls (Fig. 6). This is not surprising given that post-fire harvest removes overstory and midstory trees which, by definition, simplifies residual canopy structure. A similar pattern is apparent for post-fire harvest treatment effects on metrics of horizontal canopy structure (Fig. 7). Harvest treatments increased the frequency of areas with low cover in single trees and small clumps relative to unharvested controls.

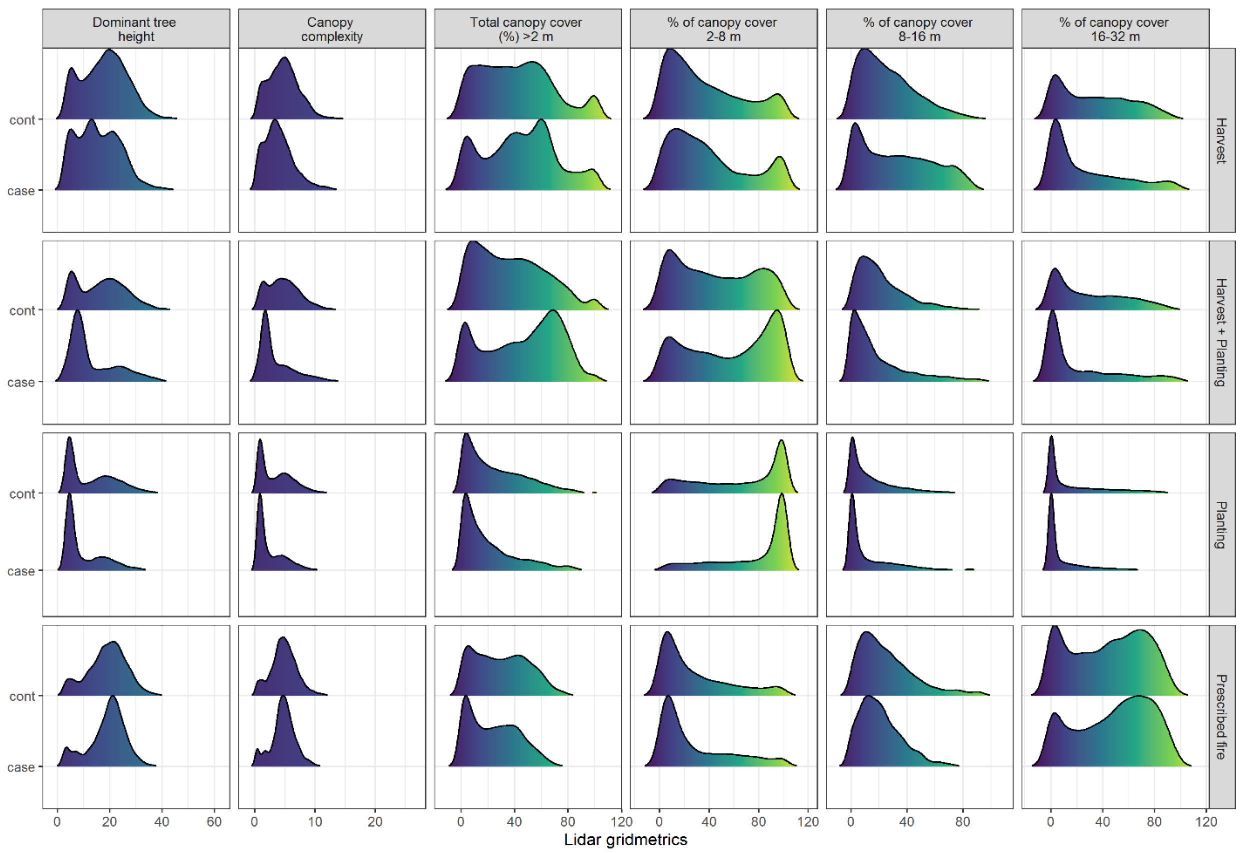

Figure 6. Distributions of LiDAR-based canopy metrics (Table 1) for paired treated (case) and untreated (cont) sites.

Forest structure differed strikingly between sites that were only planted and sites that were harvested then planted (Fig. 6). On sites that were harvested then planted total canopy cover >2 m is rapidly recovering, but not the controls, with high proportional canopy cover in the 2-8 m canopy height stratum. We interpret this as the signal of planted trees growing into sizes detectable with airborne LiDAR. In contrast, on the planting only sites, there is low total canopy cover in both planted and control area (Fig. 6), and only negligible differences between the planted sites and their paired controls. This is almost certainly due to the high drought stress and low potential productivity of the planting only sites compared to the harvest and planting sites (Fig. 5). The harsh environmental conditions on the planting only sites limit post-fire forest development through low seedling survival, low seedling growth rates, or a combination thereof.

Prescribed fire was used at sites with more residual large trees than the other post-fire treatments. This is apparent in the relatively high dominant tree height and the high proportional distribution of canopy cover in the 16 to 32 m height stratum (Fig 6). This is consistent with the lower burn severities characteristic of sites selected for post-wildfire prescribed fire (Fig. 5). Compared to the paired untreated controls, prescribed fires functioned to further decouple the canopy fuels (16 to 32 m height stratum) from the surface and understory fuels. This is evident by the more pronounced right mode in the 16 to 32 m height stratum in the sites treated with prescribed fire compared to their controls, and the leftward shift of cover in the 8-16 m height stratum. The horizontal pattern metrics (Fig. 7) show a similar result for prescribed fire: compared to paired untreated controls, prescribed fire increased the proportion of canopy cover in widely spaced individual trees and increased the total area of canopy openings. Thus, the prescribed fire reduced canopy bulk density and contagion of canopy fuels and reduced residual ladder fuels. Combined with consumption of surface fuels (a self-evident, though here unmeasured, outcome of prescribed fire), the effect of post-fire prescribed fire was to create a more crown-fire resistant stand structure conducive to a stabilizing feedback role for future wildfires (Agee and Skinner 2005).

Twelve to 32 years after wildfire, post-fire treatments have a modest but detectable effect on forest structure relative to carefully paired untreated controls. However, fire severity has a much stronger control over forest structure than post-fire treatments (Fig 5). Post-fire treatments that include harvest have a simplifying effect on forest canopy structure, but this effect is subtle given the stronger signal of wildfire burn severity. Site environmental characteristics govern the influence of planting on post-wildfire structural development. Planting on moist, productive sites leads to rapid recovery of total canopy cover and high concentration of this cover in the 2 to 8 m height stratum, while planting on stressful, dry sites has little detectable effect on forest structure in the first three decades after fire, presumably because of lower survival and slower growth of planted seedlings. Post-wildfire prescribed fire treatments had structural outcomes consistent with sustaining future surface fire regimes beneath a simple canopy structure of widely spaced trees in the large/tall tree size class interspersed among small tree clumps and large openings. In those sites, the back-to-back combination of an initial low severity wildfire followed by prescribed fire within five years promoted a stabilizing fire-forest structure feedback in which future fires should maintain forest structure (Larson and Churchill 2012).

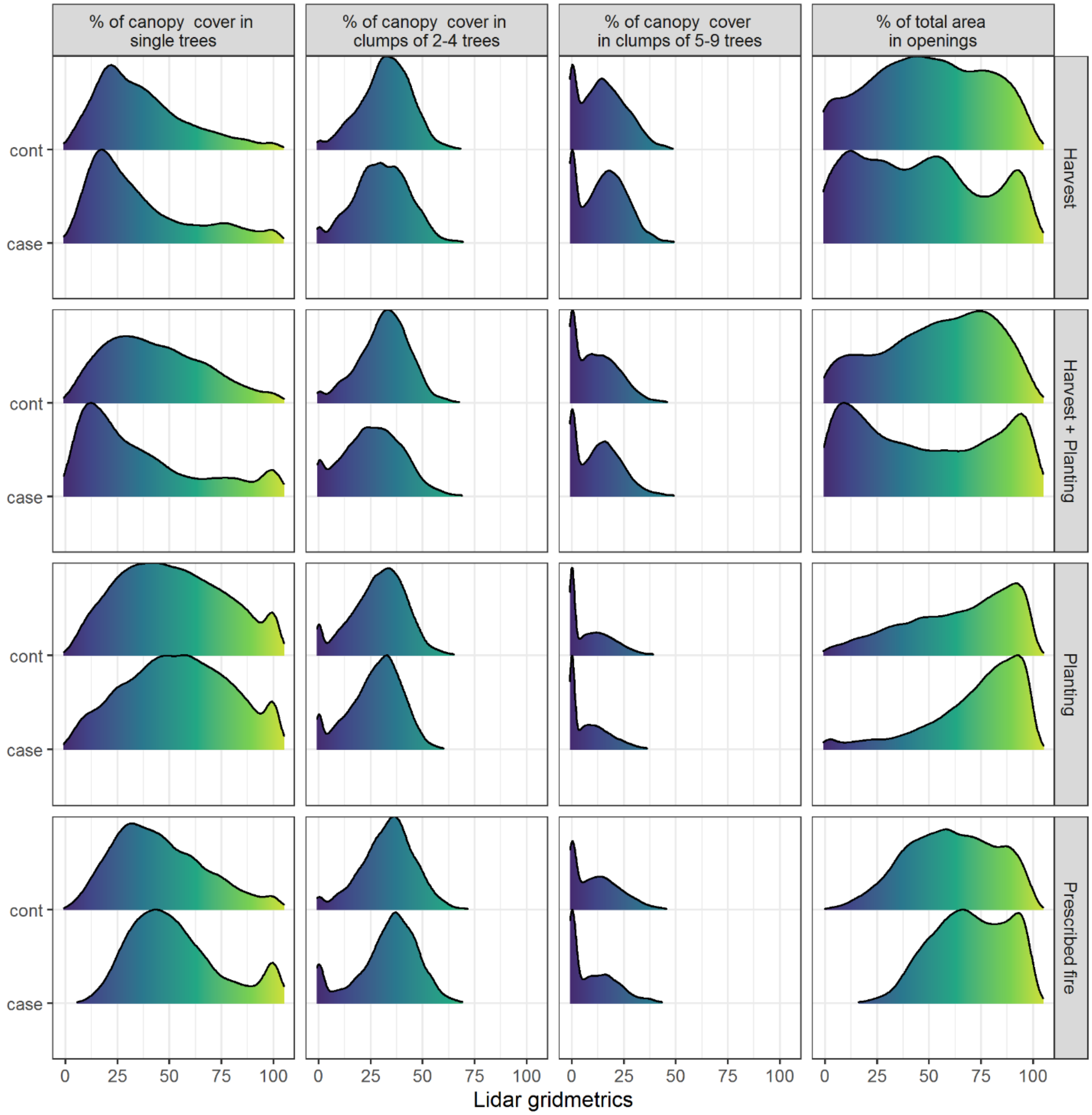

Figure 7. Distributions of lidar LICO metrics (Table 1) for different post-fire treatments (case) and matched controls (cont).

Objective 2: Drivers of fire severity

Research questions

- How does the biophysical environment, annual climate, and daily weather influence burn severity in fires that occurred from 2001-2016?
- How do previous burn severity and time since fire interact with the biophysical environment, annual climate, and daily weather to influence burn severity in reburns?
- Do local fuel treatments influence burn severity? What types of pre-fire and post-fire management treatments decrease or increase burn severity in subsequent fires?

Methods

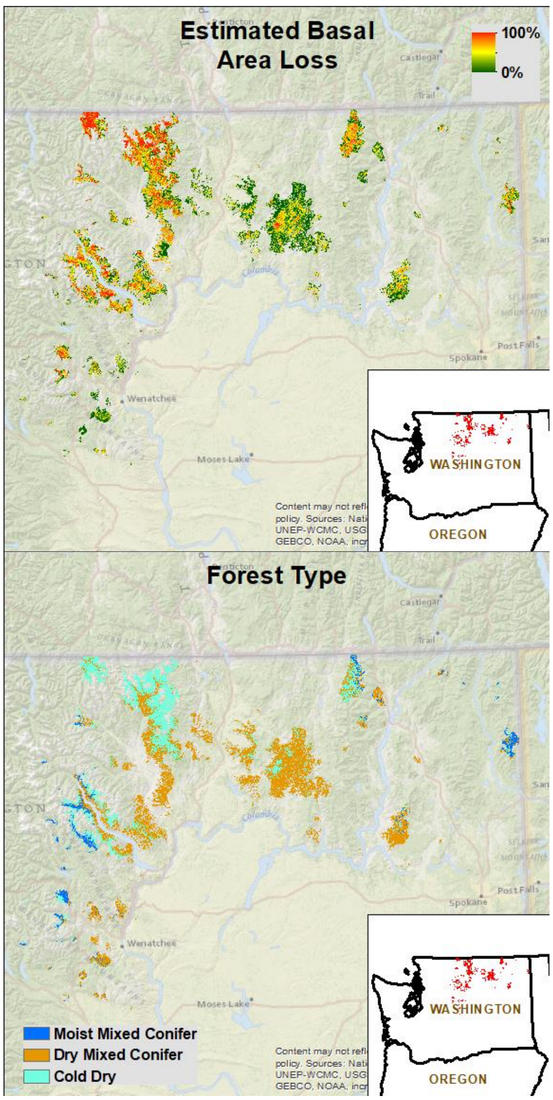

Figure 8. (Top) Burn severity of fires occurring from 1984-2016, with the most recent burn severity shown. (Bottom) Three conifer forest potential vegetation groups, shown within burned areas in the study area.

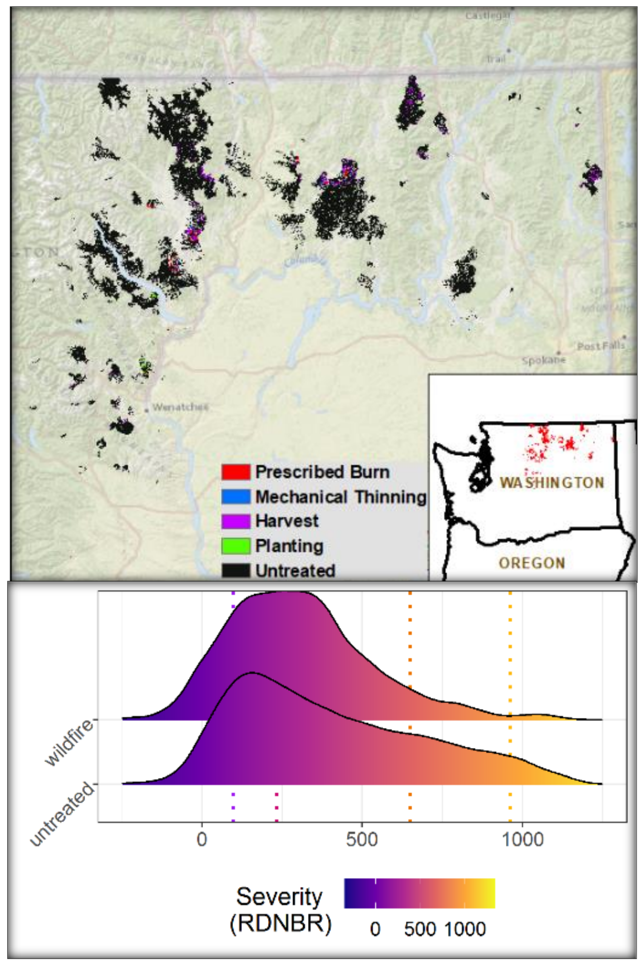

Figure 9. (Top) Management treatments within burned areas. (Bottom) Burn severity distributions for untreated reburns (e.g., burned by a previous wildfire), and for untreated fire in long unburned areas. Reburns have less of their RdNBR distribution in high (orange) and stand-replacing (yellow) categories.

Response and predictor data

Fire perimeters from the US National Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al. 2007), WA DNR, and United States Forest Service (USFS) were used to identify areas that had burned between 1984-2016, in fires ≥121 ha in size. Burn severity was mapped using the Relative difference Normalized Burn Severity Ratio (RdNBR; Miller and Thode 2007; Miller et al. 2009), which provides a relative accurate measurement of changes on the ground due to fire in northeastern Washington (Cansler and McKenzie 2012). We calculated RdNBR in Google Earth Engine, using composites of pre-fire and post-fire images, following the methods of (Parks et al. 2018).

All burn severity data used as a response was from fires that took place between 2001-2016 reflecting availability of fire weather data (see below). We consider a fire a "reburn" if it burned an area burned in a previous fire between 1984-2015. Fires from 1984-2000 were excluded from the response because we could not assign fire weather data before that year (see below). Fires with <12 ha in forested areas (based on the WA DRN forest mask) were also excluded.

We used four major types of predictor data. Temporally varying daily fire weather and yearly antecedent climate data (i.e., climate anomalies); spatially varying data describing biophysical setting, topography, and forest structure; fire history (time since and severity of last fire); and management history, including pre-fire management and post-initial fire/pre-reburn treatments.

Analysis

We used random forest (RF) modeling (Breiman 2001) to predict RdNBR. For this analysis, we sampled RdNBR and associated predictor data with a 270 m grid to create a subset of data for modeling. We modeled burn severity in long unburned areas separately from reburns. Management treatments were excluded and are addressed in a separate analysis below. Each model predicted occurrence of three burn severity classes: refugia, restorative, and high-severity (Table 1). RF analyses was conducted in R (R Core Team 2020). RF models were fit using the "ranger" package (Wright and Ziegler 2017), and the caret package (Kuhn 2008, 2020) was used for cross validation and meta-parameter tuning.

Management treatments only took place on a small portion of the study area landscape (Figure 9). Because of their small areas, and relatively small sample size, we did not include them in the landscape scale modeling. In treated areas, a census of the 30-meter pixels (0.09 ha) in all treated areas were compiled. Controls—untreated wildfires and untreated reburns—were drawn from the same dataset as used in the RF modeling above, sampled on a 270 m grid. To assess the impacts of treatments on fire severity, we test for differences between treated and untreated controls, after subsampling treatment and controls to match bioclimatic setting and fire weather for each treatment type. To match the distributions of the controls to each treatment type we "trimmed" the control observations that were outside the range of the treatment values of ERC, 1000h fuel moisture, FRS, and CWD. Second, we took a random subsample of 3000 treatment points, and 6000 control points. For post-fire pre-reburn treatments, we also matched previous fire severity and time between fires. If there were fewer than 3000 treatment points available, then we used all available points from that treatment type.

Results and Discussion

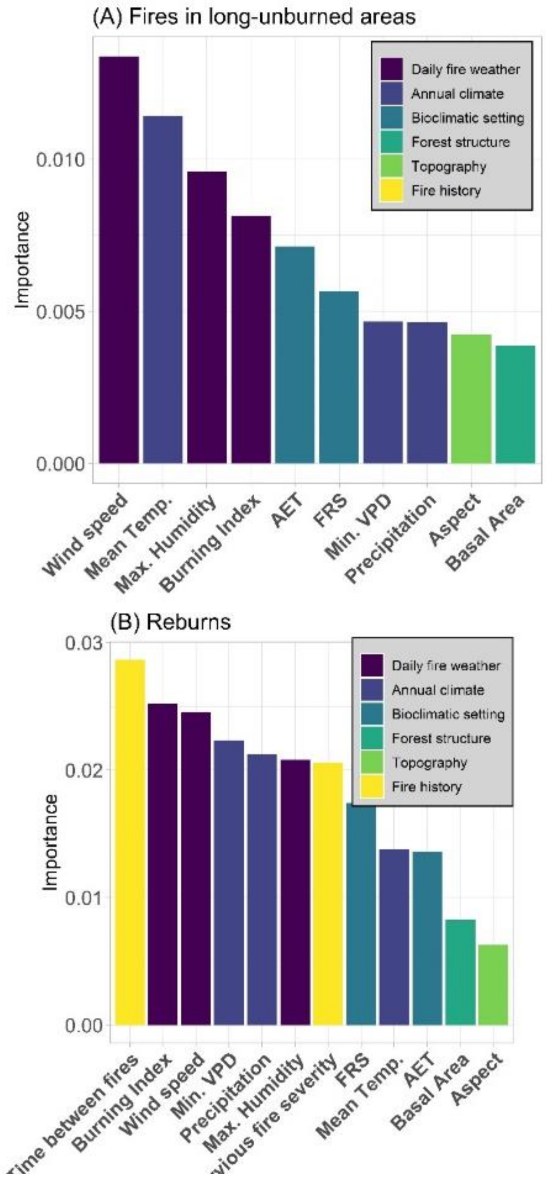

Figure 10. Variable importance plot from Random Forest models predicting burn severity (RdNBR) for fire in long-unburned areas (top) and reburns (bottom). Response data are from wildfires that occurred between 2001-2016. Reburns were previously burned between and 1984-2015. The study area was in northeastern WA, USA.

Daily fire weather and annual climate variables were top predictors in both models (Fig. 10). In reburns, the time between fire was the most important predictor, and previous burn severity also influences subsequent burn severity (Fig. 10). Bioclimatic setting was less important than annual climate or fire weather, but AET and the FRS consistently influence burn severity in both models. Aspect and pre-fire live basal area, which vary over relatively small scale, were the least important predictors in both models.

Partial dependence plots (not shown) revealed that the probability of high severity increases when relative humidity was low, the burning index was high, and when annual VPD anomalies were high. Relationships with other weather and climate variables, including daily wind speed, annual mean temperature, annual perception either did not follow the direction expected (e.g., very high wind speeds were associated with lower probability of high severity fire) or were not monotonic. Thirty-year mean AET and the FRS both had a negative association with the probability of high severity fire while pre-fire basal area and north aspects had a positive association with high severity. Predicted probabilities for fire refugia generally showed the opposite relations with predictors than was observed for high severity.

The time between fires was the most important predictor or reburn severity (Fig. 10). High severity was more likely from 14-21 years after fire, while the probability of fire refugia decreased sharply about a decade after fire. Areas with >25% basal area lost in a previous fire were unlikely to burn with high severity, and areas with >75% basal area loss were likely to be fire refugia in a subsequent fire. Relationship with daily weather variables were in the opposite direction expected for reburns, with BI and daily wind speed showing negative associations with high severity and positive associations with fire refugia. Unlike fires in long-unburned areas, reburns showed strong unidirectional relationships with annual VPD and precipitation anomalies, which increased and decreased the probability of high severity, respectively. Relationships with FRS, pre-fire basal area, and aspect were consistent with those for long-unburned areas.

Most pre-fire treatments significantly decreased burn severity. The exception was in recent planting (≤10 years before fire), which increased burn severity when they burned. The RdNBR distributions show that treatments not only have lower model burn severity (distibution peaks) but that the high severity tail, where estimate basal area mortaltiy is 100%, decreases or is not present in most treated areas (Fig. 11). The strongest effects of treatments occured in areas treated with prescibed fire, either alone or in combination with other treatments. Most prescribed fire areas manifiested as either unburned refugia or burned with low severity.

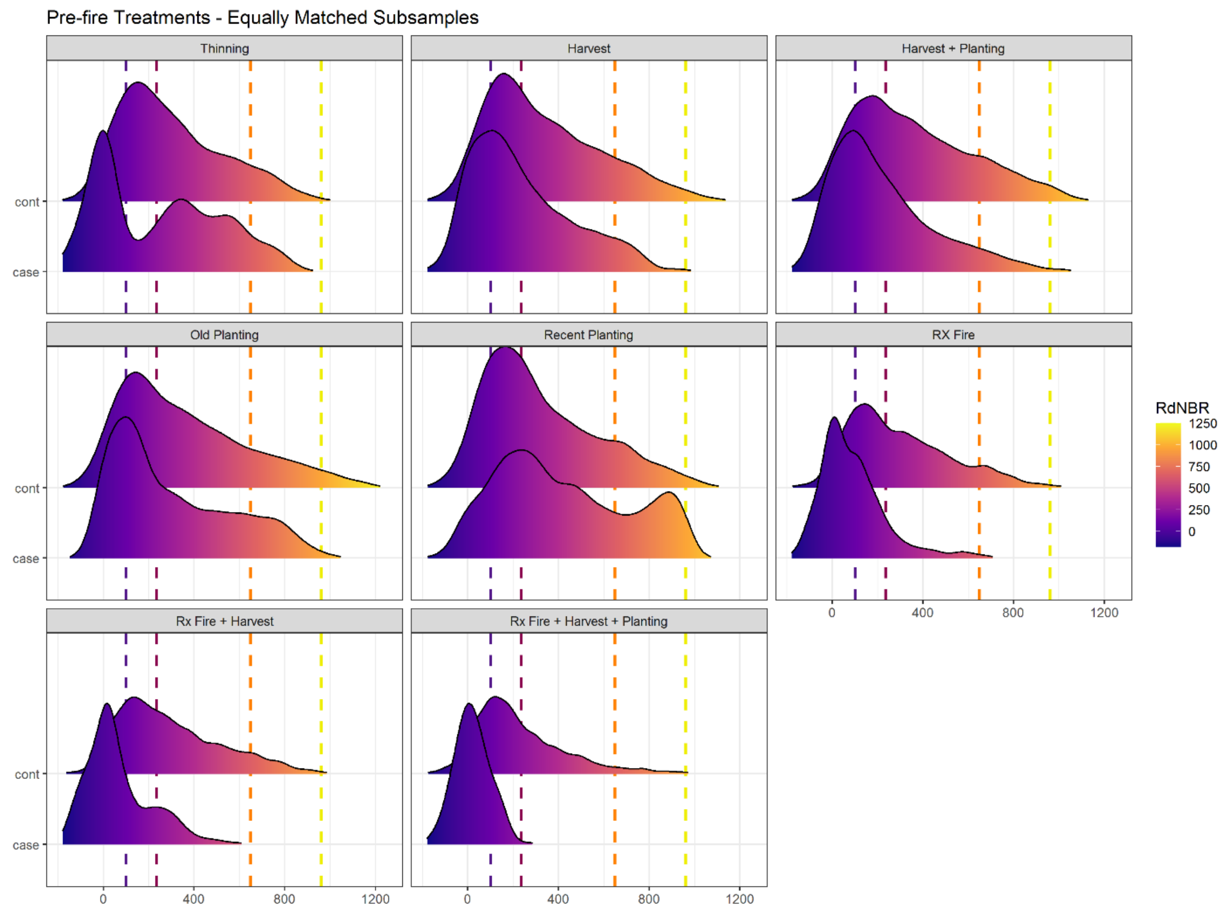

Figure 11. Pre-fire treatments and untreated controls burn severity distributions. Ridgeline plots showing the frequency distribution of the Relative differenced Normalized Burn Ratio (RdNBR), a measurement of burn severity, for untreated areas (controls) and each silviculture or fuel treatment (cases), for match equally sized subsamples in areas that were treated before fire. Vertical dashed lines correspond with the thresholds between unburned refugia and low severity (dark purple), low and moderate severity (magenta), moderate and high severity (orange), and stand replacing (yellow).

Post-fire pre-reburn forest management strategies only weakly influence on burn severity (Fig. 12). Harvest weakly increased burn severity, while harvest and planting decreased severity, mostly by decreasing the frequency of occurrence of stand-replacing fire. The planting results were equivocal. Note that the sample sizes for post-fire pre-reburn treatments were generally smaller than pre-fire treatments, with post-fire harvest, in particular, having small number of pixels, unique treatments, and burn periods to assess.

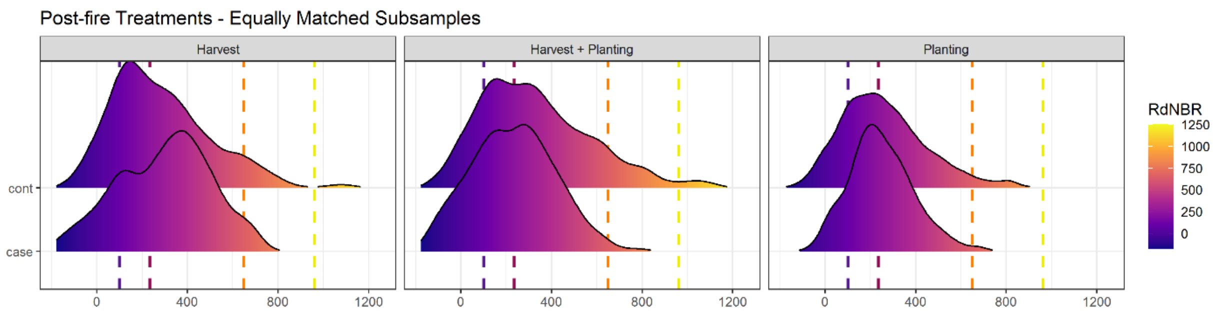

Figure 12. Post-fire pre-reburn treatments and untreated controls burn severity distributions or the reburns. Ridgeline plots showing the frequency distribution of the Relative differenced Normalized Burn Ratio (RdNBR), a measurement of burn severity, for reburn areas (controls) and each silviculture or fuel treatment (cases), for match equally sized subsamples in areas that were treated before fire. Vertical dashed lines correspond to those shown in Fig. 11.

Previous wildfires fires and previous prescribed fires decreased the severity of subsequent wildfires. Previous fires strongly decrease the severity of subsequent fires for the first decade after fire. In other regions, including the Gila National forest in New Mexico, the south-central Sierra Nevada and the Klamath Mountains, previous fire increase the probability of high severity fire when they reburn more than a decade after the previous fire (Thompson et al. 2007; Collins et al. 2009; Holden et al. 2010; Halofsky et al. 2011, Parks et al. 2014). We did not observe any evidence of positive feedbacks between previous fires and subsequent fire severity. To the contrary, high severity was consistently less likely in reburns, even when fire weather was severe (e.g., high burning index or low relatively humidity), and even ≥25 years after the previous fire. High burn severity was most likely to occur in reburns in stands with a low fire resistance score: high elevation subalpine forests where dominant trees species have thin bark, flammable foliage, and undergo little self-pruning (Stevens et al. 2020) and are therefore more susceptible to fire-caused injury and mortality (Cansler et al. 2020).

We found that management treatments that include prescribed fire were most effective at decreasing the severity of subsequent fires. These results are consistent with previous research in our study area (Lyons-Tinsley and Peterson 2012; Prichard and Kennedy 2014), and elsewhere in western North America (Kalies and Yocom Kent 2016). Most of the other fuel treatments, including thinning, harvest, and harvest combined with planting also decreased the severity of fires occurring in long-unburned areas. When recent plantings burned, they often burned with higher severity, probably due to the lack of fire resistance traits of young conifers: thing bark and low crows result in more severe fire injury in small conifers (Hood et al. 2018; Cansler et al. 2020). Previous research has found both positive (Zald and Dunn 2018) and negative (Lyons-Tinsley and Peterson 2012) associations between young stands and fire severity. We did not see evidence for increase fire severity in plantings that took place after an initial fire and then were subsequently reburned (Figure 5). Therefore, we reiterate the findings of Lyons-Tinsley and Peterson (2012): treatment of surface fuels before planting occurs can provide an important dampening effects on subsequent fire severity in young plantations.

Objectives 3, 4 & 5: Post-Fire Landscape Evaluations and Prescriptions

Research Goals and Study Area

- Evaluate how wildfires in four sub-watersheds affected landscape level structure, composition, and pattern of vegetation relative to historical and future range of variation envelopes (HRV and FRV).
- Evaluate how different data sources and reference condition datasets affect our ability to assess landscapes and evaluate departure.
- Synthesize application of our results to management in post-fire landscape prescriptions.

Four sub-watersheds (Hydrologic Unit Code 12) that burned in 2014, 2015, or 2017 were selected for pre- and post-fire departure assessments (Fig. 13) based on four factors. The sub-watersheds were chosen to span a gradient of fire severity that ranged from predominantly large patches of high severity fire to predominantly moderate and low severity fire (Fig. 14).

We illustrate our methods and results using the Benson Creek and Scatter Creek watersheds, which occupy opposite ends of the fire severity gradient (Fig. 14). Results from the other two sub-watersheds are similar and will be included in ensuing journal articles.

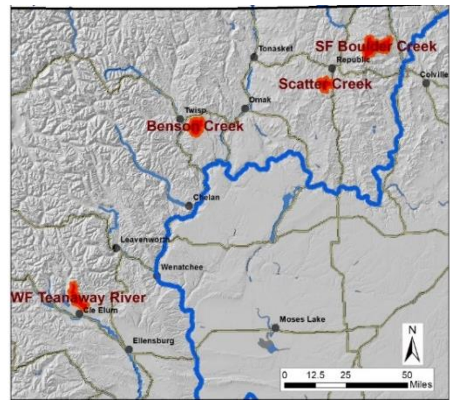

Figure 13. Location of four sub-watersheds selected for pre- and post-fire departure analysis.

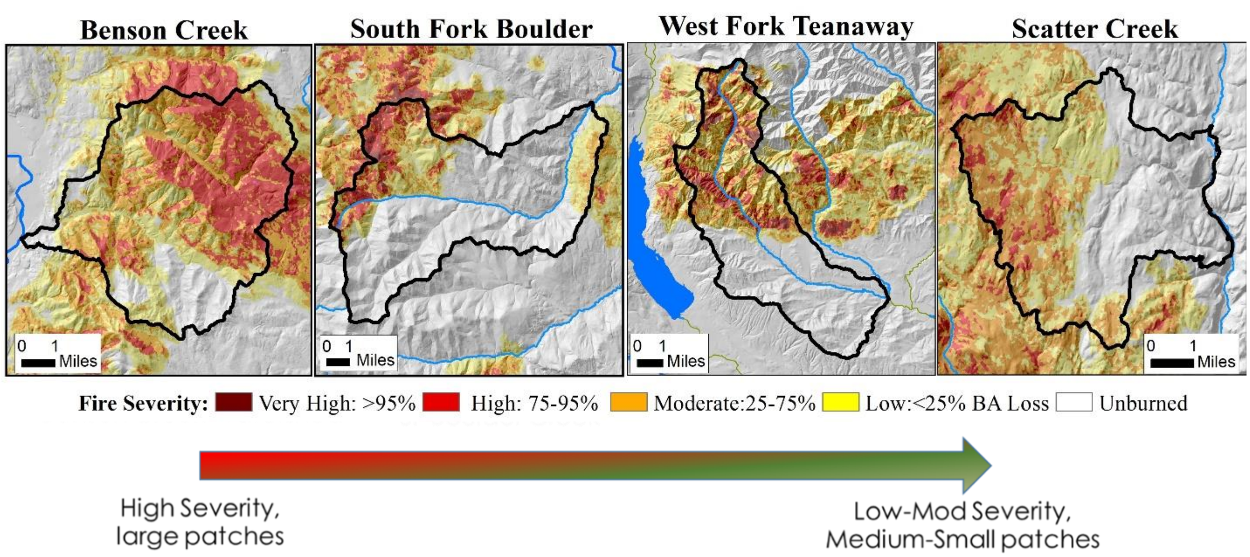

Figure 14. Fire severity (Basal Area Loss) maps for fires in four sub-watersheds. Note the gradient from predominantly large patches of high severity fire on the left to predominantly moderate and low severity fire with small patches of high severity fire on the right.

Methods

Pre and Post Fire Vegetation Attributes

Photo-interpretation was used to collected pre and post fire vegetation attributes using the protocols and system developed by Hessburg et al. (1999, 2013) that is currently used for restoration planning on the OWNF (USFS 2012). Digital, high resolution (40 cm) stereo imagery was obtained from the Washington Department of Natural Resources. Pre-fire successional patches (polygons) were delineated for each sub-watershed based on vegetation and topography with a 4-ha minimum size. Photo-interpreted (PI) raw attributes such as canopy cover, overstory and understory size class, and dominant species were then estimated for each successional patch. LiDAR derived canopy cover and height rasters were manually used by the photo-interpreters to improve the consistency of visual interpretation.

Using these raw attributes and classification criteria, three primary derived attributes were calculated for each successional patch. Physiognomic type was the first attribute used in order to assess changes in the pattern of forest and non-forest vegetation. Classes include forest (canopy cover 40% or greater), woodland (canopy cover 10-30%), herbland, shrubland, or non-forest (barren, water, or anthropogenic types). Second, successional patches were classified into six structure class based on combinations of two classes of canopy cover: open (<50% cover), and closed (50%+ cover); and three size classes: small (0-24.5 cm), medium (25-49cm), and large (50+cm). Size class was derived from overstory and understory tree size raw PI attributes, weighted by the relative cover of the understory and overstory layers. An open class comprises patches with small trees and less than 50% cover, as well as any patch with less than 10% canopy cover regardless of tree size class or physiognomic type. Third, tree species composition was classified into cover types based on overstory and understory species using a classification key described in Hessburg et al. (1999).

Class and landscape metrics such as percent land, mean patch size, largest patch size, mean nearest neighbor, contagion, and aggregation were then generated for each of the three derived attributes. Patch size distributions were also generated. This process was repeated for the burned area of each sub-watershed using the pre-fire polygons and raw attributes during photo-interpretation as a reference to minimize re-measurement error. Additional derived attributes such as habitat for focal wildlife species, insect vulnerability, and fire behavior indices (see Hessburg et al. (2013), as well as associated class and landscape metrics, were also generated and analyzed. However, they are not reported here as they are derived from the same raw attributes and do not add significant additional information that is relevant to the objectives of this study.

Departure Analysis

To assess departure, class and landscape metrics from the pre and post-fire sub-watersheds were compared with reference sub-watersheds. The historical aerial photograph dataset from the Interior Columbia Basin Ecosystem Management Project (Hessburg et al., 1999) was used for this purpose, and was collected using the same PI protocols. For each sub-watershed, historical data from 10-16 reference sub-watersheds within the same ecological sub-region (Hessburg et al. 2000) formed the historical range of variation (HRV). A second set of 10-16 reference sub-watersheds from a warmer and drier ecological sub-region that match the projected future climate of the target sub-watershed were used for the future range of variation (FRV). See

Hessburg et al. (2013) for a full description of this process. Changes in landscape conditions caused by the wildfires were quantified by analyzing the differences between pre- and post-fire metrics and how they compare to the 80^{th} percentile HRV and FRV ranges (departure). Metrics for the three primary derived vegetation attributes were analyzed for pre- and post-fire departure using a combination of approaches. Many different class and landscape pattern metrics were analyzed. The most parsimonious set that described the key effects of the fires were selected to be reported. For physiognomic type, the proportion of the landscape occupied by each type (percent land) and mean patch size of each type was graphically compared to the HRV and FRV ranges to assess which types were below, within, or above the reference ranges before and after the fire. Only percent land departures for cover types are presented. For forest structure class, the same method was used to assess changes in percent land and mean patch size. The extent that fires sustained large tree classes was evaluated using these data. Pre- and post-fire cumulative patch size distributions of all structure classes were also generated and compared to same distributions from the HRV and FRV sub-watersheds.

We assessed changes to forest structure caused by fire in relation to reference ranges of variation using a principal components analysis (PCA) ordination. We selected six photo-interpreted (PI) input variables to define the PCA axes: total canopy cover, overstory canopy cover, number of canopy layers, overstory tree size, understory tree size, and snag density. The units of measurement were individual forested PI stand polygons for pooled HRV, FRV, pre-fire, and post-fire datasets, with contributions to the PCA weighted by polygon area. We visualized data in PC-space by plotting area-weighted centroids of HRV and FRV watersheds overlaid with pre- and post-fire centroids for analysis watersheds.

Alternative methods for departure analysis

Two alternative methods of conducting departure analyses were employed. The first alternative approach was developed for regional assessments of restoration need (Haugo et al. 2015, DeMeo et al. 2018). It utilizes vegetation data from 30m GNN grids (Ohmann et al. 2011) to obtain structure class data. Reference ranges come from state and transition models developed for Landfire Biophysical Settings (https://www.landfire.gov/bps-models.php).

The second alternative approach uses reference conditions from state and transition models developed for the Integrated Landscape Assessment Project (Hemstrom et al. 2014). Models were further developed for Northeast Washington for the Colville National Forest Plan Revision (USFS 2019). Structure class data was obtained from pre and post-fire Digital Aerial Photogrammetry (DAP) using high resolution (40 cm), stereo imagery and LiDAR ground models (Strunk et al. 2019). DAP produces similar grids of canopy cover and tree height layers as LiDAR, but with reduced accuracy. Tree size for structure classes (overstory diameter) was modeled from field inventory plot data and DAP layers. Both of these methods are more basic than the PI based approach. Only percent land of structure class is evaluated against the HRV. No FRV, pattern metrics, or species composition metrics are included. In addition, structure class information is based on a much finer grain size than the PI approach (20 or 30 m raster layers vs. 4+ ha polygons). Due to data limitations, these alternative methods could only be conducted in two sub-watersheds: Scatter Creek and South Fork Boulder.

Results and Discussion

Benson Creek

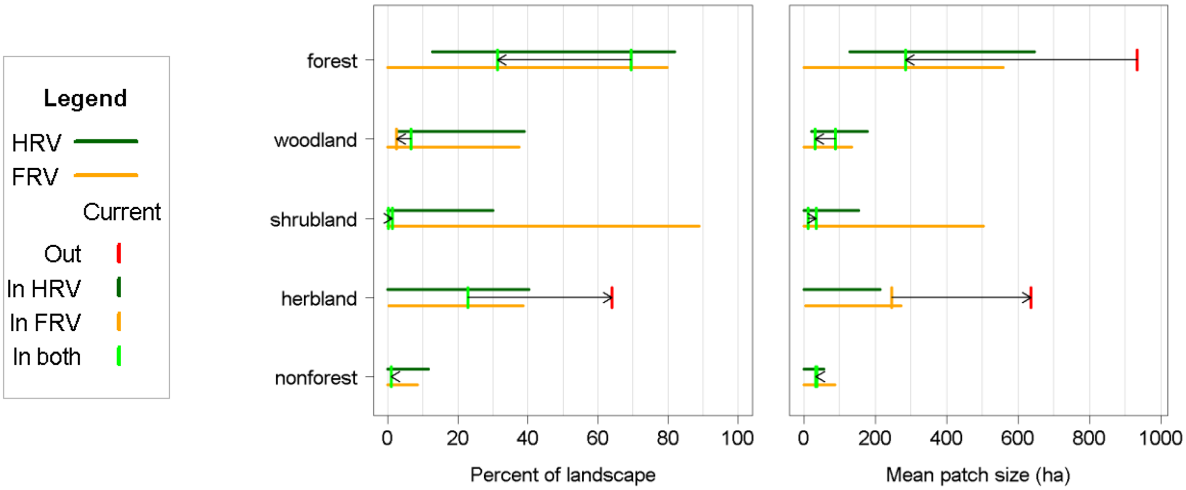

Figure 15. Percent land (left) and mean patch size (right) for physiognomic types in the Benson Creek sub-watershed. Arrows show the direction of change from pre- to post-fire conditions.

The large, high severity patches created by the Carlton Complex fire had a major impact on landscape pattern in Benson Creek (Figures 15, 16). The fire dramatically reduced the percent land (PL) and mean patch size (MPS) of forest and increased herbland above the HRV and FRV. It also converted most of the woodland to herbland thereby pushing it to the lower end of HRV-FRV. Similarly, the PL and MPS for most of the forest structural classes were pushed to the lower end of HRV-FRV, especially the large-closed and medium-closed classes (Figure 17). Conversely, the open class was shifted towards the upper end for both PL and MPS.

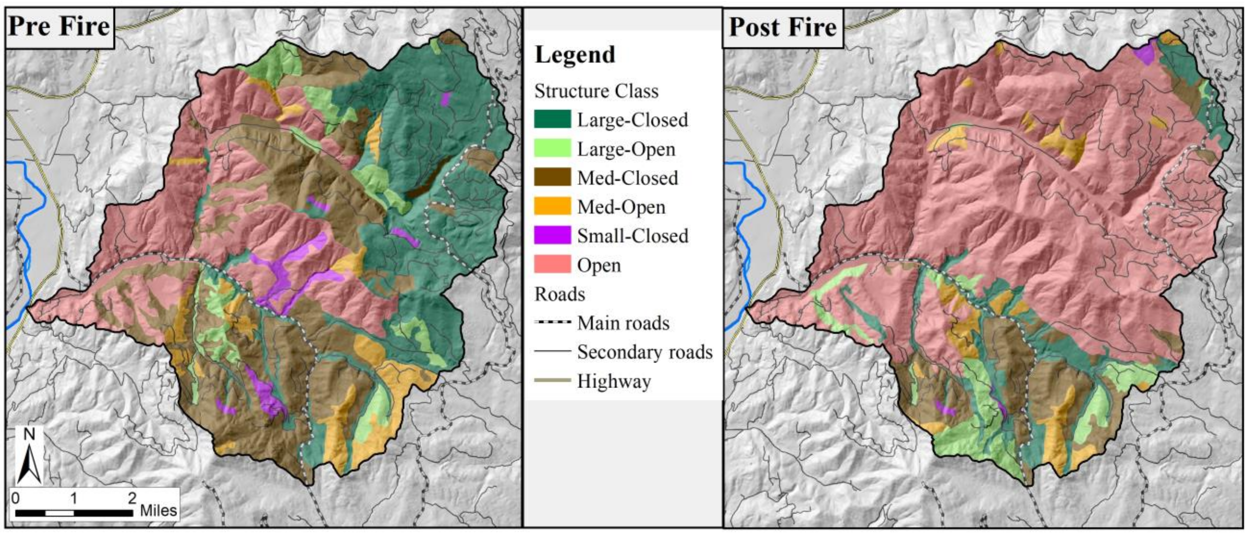

Figure 16. Pre- (left) and post-fire (right) forest structure classes in Benson Creek.

Overall, the fire shifted forest structure in the direction of the future range of variability, but went right to the lower edge of forest cover (Figure 17C). The large patches of high severity coarsened and homogenized landscape pattern, reducing the proportion of smaller and medium patches and creating a very large open patch that occupies close to 70% of the landscape (Figure 17D) Finally, the fire reduced ponderosa pine and Douglas-fir cover types and converted these sites to herbland. No shifts from one forest cover type to another were detected.

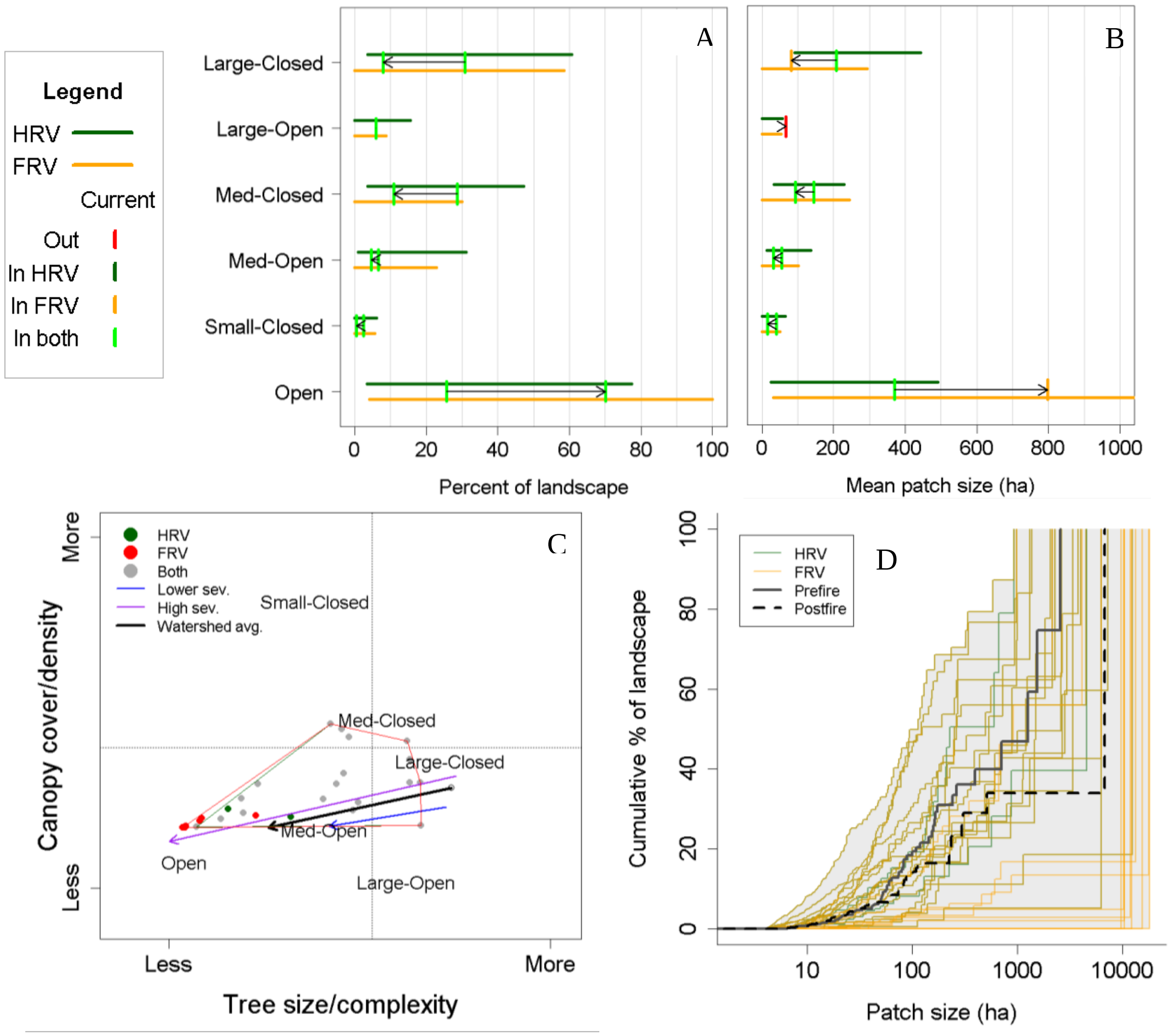

Figure 17. Percent land (A) and mean patch size (B) for forest structure classes in the Benson Creek sub-watershed. Arrows show the direction of change from pre to post-fire conditions. Panel C shows principal components analysis of 6 forest structural attributes. Green and red dots show area-weighted centroids of HRV and FRV sub-watersheds. Arrows display shifts in Benson Creek caused by fire. Panel D displays cumulative patch size distribution of structure classes for pre- and post-fire successional patches compared with reference sub-watersheds.

Scatter Creek

The predominantly moderate and low severity fire that burned through 56% of the Scatter Creek sub-watershed shifted some attributes of vegetation towards more climate adapted conditions, while moving other attributes away. The PL of the forest physiognomic type was reduced to below the HRV, but well within the FRV (Figure 18). Similarly, PL of herbland and woodland increased above HRV, but within FRV. The fire greatly reduced MPS of forest by breaking up large patches of forest, but only slightly increased the MPS of herbland and woodland. The primary effect of the fire on forest structure classes was to shift medium-closed PL and MPS from the upper end of the HRV-FRV to the middle of the range (Figures 19, 20). The fire converted this class to large-open, medium open, and open classes, but did not significantly increase the MPS of these classes, which tend towards the lower end of the HRV-FRV. While only marginally affected by the fire, large-closed occupies less than 10% of the landscape and is at lower end of the FRV and below HRV-FRV for MPS. Large-open is also relatively rare.

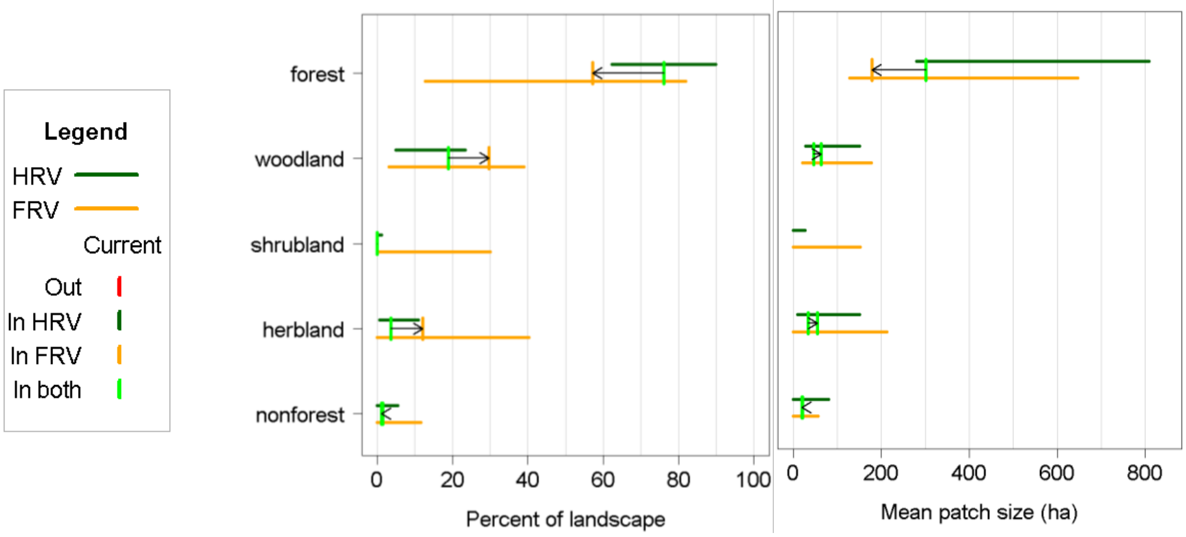

Figure 18. Percent land (left) and mean patch size (right) for physiognomic types in the Scatter Creek sub-watershed. Arrows show the direction of change from pre to post-fire conditions.

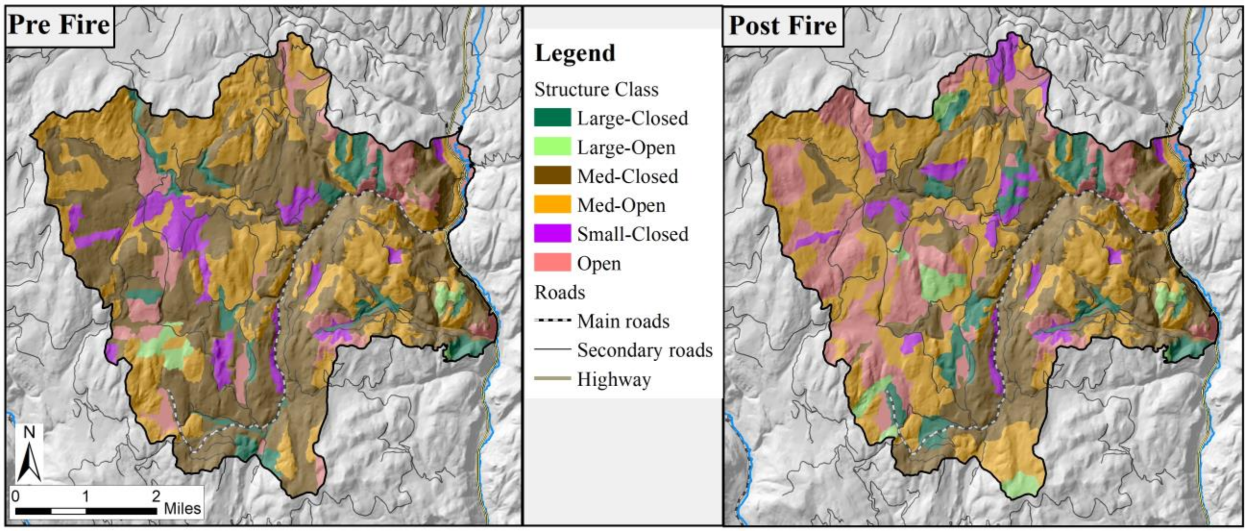

Figure 19. Pre- (left) and post-fire (right) forest structure classes in Scatter Creek.

Overall, the fire shifted forest structure in the direction of lower canopy cover and reduced tree size and canopy complexity (Figure 20C). The landscape was below HRV for tree size and canopy complexity before the fire, but at the upper end of both HRV and FRV for canopy cover. The fire further fragmented the sub-watershed, which was already at the smaller end of the patch size distribution (Figures 19, 20D). The fine grain of fire severity (Figure 14D) broke up or disconnected pre-fire medium and larger patches (Figure 19), while the small patch size of high severity fire did not create new medium and large sized patches. The overall result is a fragmented landscape that is at the outer edge of the HRV-FRV pattern envelop (Figure 20D).

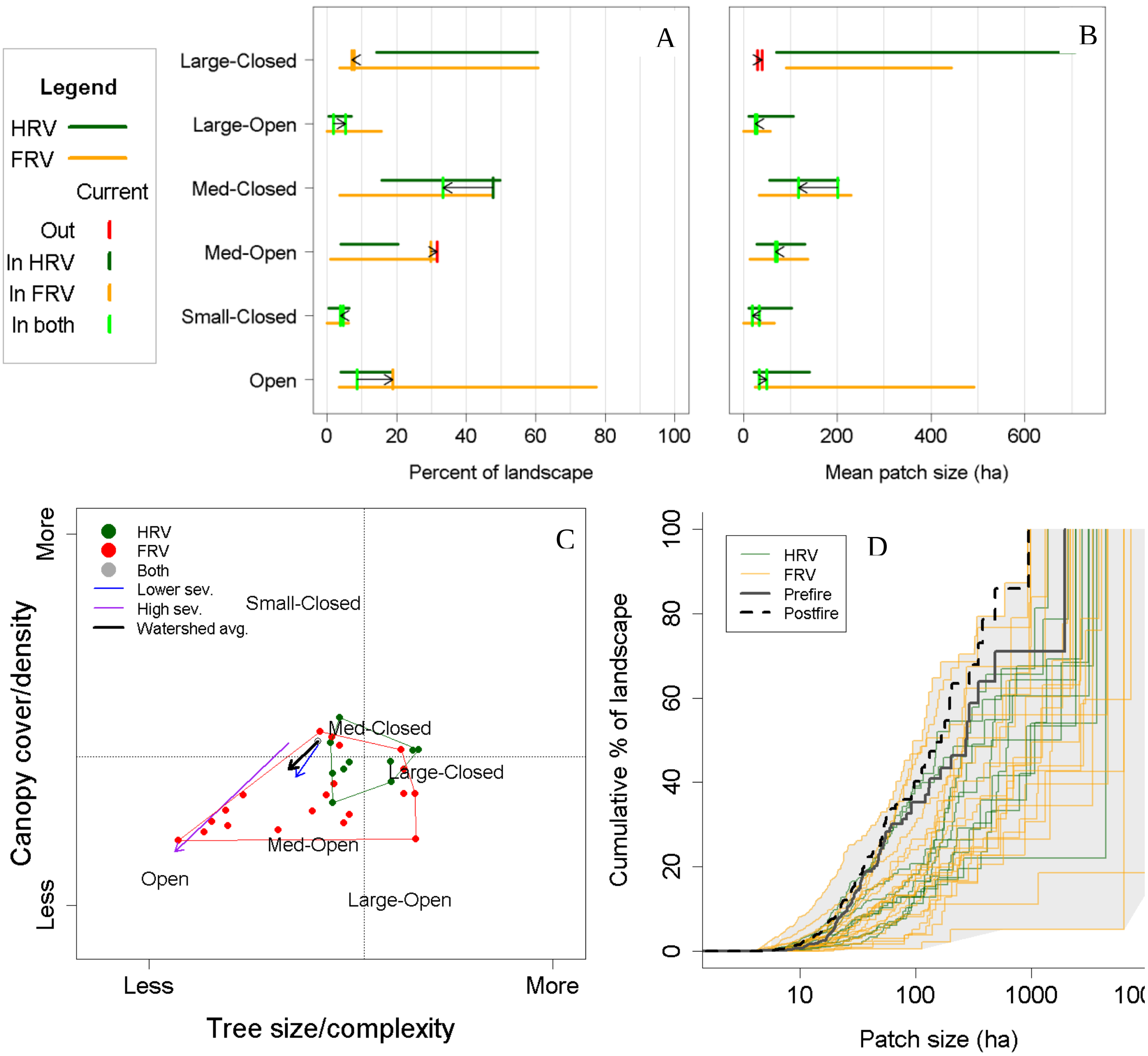

Figure 20: Percent land (A) and mean patch size (B) for forest structure classes in the Benson Creek sub-watershed. Arrows show the direction of change from pre to post-fire conditions. Panel C shows principal components analysis of 6 forest structural attributes. Green and red dots show area-weighted centroids of HRV and FRV sub-watersheds. Arrows display shifts in Scatter Creek caused by fire. Panel D displays cumulative patch size distribution of structure classes for pre and post-fire successional patches compared with reference sub-watersheds.

Alternative methods for departure analysis

The three different methods of conducting post-fire departure analyses resulted in different conclusions regarding which structure classes are departed and the degree of departure (Table 3). The DAP and PI methods found roughly similar proportions of post-fire structure classes, but substantial differences exist in the HRV ranges between the ILAP state and transition models and the historical photo dataset from the Interior Columbia Basin Ecosystem Management project. GNN had different post-fire conditions, and the Landfire BPS HRV ranges are also quite different. A major source of difference in the HRV ranges is the different PVT/BPS layer.

Table 3. Post-fire departure analysis results for two sub-watersheds using 3 different methodologies. Yellow rows indicate structure classes that are below the HRV, while orange are above. The HRV ranges for ILAP and Landfire are an average of the values by potential vegetation type (PVT) or BPS, weighted by the proportion of each PVT or BPS in each sub-watershed.

Sub-Watershed	Departure Method	Structure Class	Post-Fire % of sub-watershed	HRV-Low	HRV-High
Scatter	PI - ICBEMP	Early	22%	5%	25%
Scatter	DAP-CNF-ILAP	Early	27%	10%	26%
Scatter	GNN-Landfire	Early	1%	12%	14%
Scatter	PI - ICBEMP	Late Closed	7%	14%	61%
Scatter	DAP-CNF-ILAP	Late Closed	12%	3%	34%
Scatter	GNN-Landfire	Late Closed	13%	13%	15%
Scatter	PI - ICBEMP	Late Open	5%	1%	7%
Scatter	DAP-CNF-ILAP	Late Open	2%	24%	52%
Scatter	GNN-Landfire	Late Open	2%	41%	38%
Scatter	PI - ICBEMP	Mid Closed	34%	16%	50%
Scatter	DAP-CNF-ILAP	Mid Closed	40%	5%	21%
Scatter	GNN-Landfire	Mid Closed	66%	2%	3%
Scatter	PI - ICBEMP	Mid Open	32%	4%	21%
Scatter	DAP-CNF-ILAP	Mid Open	19%	2%	8%
Scatter	GNN-Landfire	Mid Open	19%	32%	30%
SF Boulder	PI - ICBEMP	Early	33%	4%	85%
SF Boulder	DAP-CNF-ILAP	Early	24%	25%	43%
SF Boulder	GNN-Landfire	Early	5%	9%	10%
SF Boulder	PI - ICBEMP	Late Closed	18%	1%	45%
SF Boulder	DAP-CNF-ILAP	Late Closed	21%	14%	40%
SF Boulder	GNN-Landfire	Late Closed	16%	23%	22%
SF Boulder	PI - ICBEMP	Late Open	4%	0%	4%
SF Boulder	DAP-CNF-ILAP	Late Open	1%	8%	16%
SF Boulder	GNN-Landfire	Late Open	6%	27%	26%
SF Boulder	PI - ICBEMP	Mid Closed	35%	4%	75%
SF Boulder	DAP-CNF-ILAP	Mid Closed	43%	20%	38%
SF Boulder	GNN-Landfire	Mid Closed	37%	17%	17%
SF Boulder	PI - ICBEMP	Mid Open	10%	2%	10%
SF Boulder	DAP-CNF-ILAP	Mid Open	11%	1%	3%
SF Boulder	GNN-Landfire	Mid Open	36%	25%	24%

Landscape prescriptions
Large wildfires rapidly reorganize the vegetation mosaic in ways that planned vegetation treatments do not (Figs. 16 and 19). Wildfires reduce the abundance of large trees and the extent and connectivity of complex canopy patches; create a lagged pulse of woody surface fuels from fire-killed branches and trees; and reinitiate, strengthen, and overturn both stabilizing (negative) and amplifying (positive) fire-vegetation feedbacks. Thus, while core principles of fire-prone forest restoration in fire-excluded landscapes apply (Hessburg et al. 2015), additional principles responsive to fire effects help post-fire management strengthen the beneficial work of wildfires, mitigate effects of uncharacteristically severe fire, and enhance adaptive ecological resilience to changing fire regimes and climate. Key principles for post-fire landscape management include:

- *Protect fire refugia and legacy large diameter trees.*
- *First entry fires after a long fire-free period create surface fuels: anticipate future fuel management needs.*
- *Use places where fire reinitiated or strengthened stabilizing feedbacks as core areas from which to grow forest landscape resilience.*
- *Differentiate irreversible conversions to non-forest due to climate-limited tree establishment from reversible transitions due to dispersal limitation.*
- *Align species composition and structure with future fire regimes and climate.*

We implemented these principles in a GIS framework (Table 4) to develop a spatial prioritization for the post-fire landscape prescriptions (Fig. 21). Landscape prescriptions incorporate additional information from the departure analysis (Figs. 15 to 20) on the abundance (or rarity) of physiognomic types and forest structure classes to further prioritize post-fire management.

No treatment is always an option. The maps in Fig. 21 are a watershed-scale guide that highlights where different post-fire management actions may be most appropriate—they are not a mandate to treat all areas in a particular category. Actual treatment locations and extent will depend on field verification, operational factors like road networks and logging systems, and human dimensions of public land management and decision making.

Benson Creek Landscape Prescription

The fire burned with very high severity, creating a single giant open patch (Fig. 16) and reducing the large tree structure classes to the edge, or outside of, the HRV-FRV envelopes (Fig. 17).

- Break up the single very large open patch (Fig. 16) by reestablishing patches of forest cover. Plant founder tree populations (North et al. 2019) of climate-adapted species in dispersal limited areas, focusing on productive north and east aspects.
- Protect planted seedling populations from reburns over the next few decades while they grow into fire resistant size classes. This may involve salvage harvest to reduce future surface fuels and creation of fuel breaks to limit future fire spread into planted patches.
- Avoid planting on sites unlikely to support forest (climate limited areas in Fig. 21).
- Most remaining medium and large tree structure is in the unburned southeast portion of the watershed (Fig 21). Consider maintenance prescribed burns and mechanical

restoration treatments in this part of the watershed to enhance resistance and resilience to future fires, increasing likelihood of maintaining what forest remains on the landscape.

Scatter Creek Landscape Prescription

Past overstory removal harvests fragmented this landscape and depleted populations of large trees before the fire. The fire compounded this land use history, increasing fragmentation (Fig. 20) and further reducing area of large tree open and closed canopy forest patches (Fig. 19).

- Prioritize protection of closed forest patches in likely climate refugia ("Structurally complex" patches in Fig 21), and recruitment from the medium to large tree size classes. This may involve creation of fuel breaks adjacent to these areas to limit future fire spread into closed canopy patches, and potentially use of variable density thinning to accelerate transition from medium to large tree closed canopy structure.
- Consolidate fragmented patches (Fig. 19) and set some current medium-open patches on a trajectory towards large-open structure. Focus work across the northern half of the watershed, anchoring treatments around "Stabilizing feedback" patches. Use combinations of "salvage from below," green tree thinning, and prescribed fire (both inside and outside burn footprint).
- Evaluate regeneration in open patches and plant climate adapted species as needed.
- Open areas are at the low end of FRV. Identify open areas for maintenance and expansion with future prescribed fire and managed wildfire.

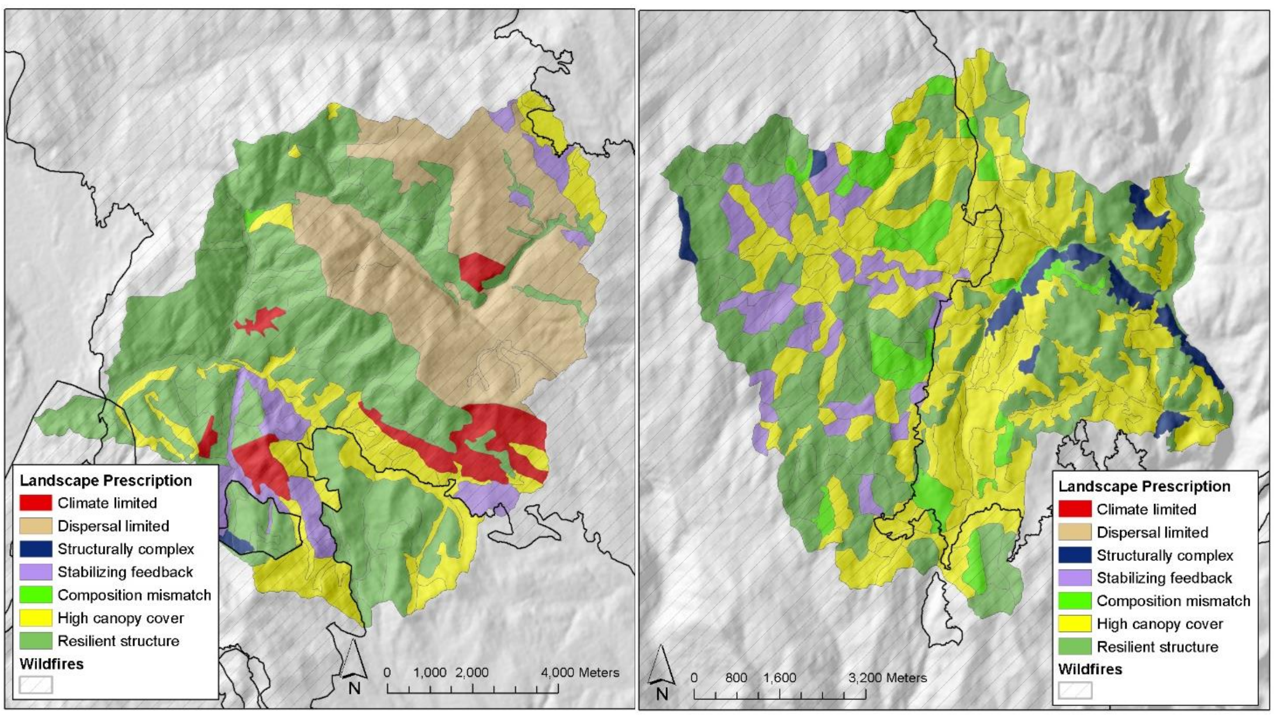

Figure 21. Spatial post-fire landscape prescriptions for the Benson Creek watershed (left) and Scatter Creek watershed (right). Landscape prescription categories are described in Table 4.

Table 4. Post-fire landscape prescription key. Patches are assigned to the first category (working down the list from one to seven) for which the relevant quantitative criteria are satisfied, resulting in a coarse-filter spatial prioritization for post-fire treatment planning (Fig. 21).

Landscape Rx category	Description, quantitative criteria, and potential treatments
1. Climate limited	High-severity patch where future moisture stress limits tree seedling recruitment—likely conversion to non-forest.
Quantitative criteria	• Fire severity: high or extra high • Future deficit: non-forest
Potential treatments	• Reburn or Rx fire • Economic salvage without planting • Invasive species management: herbicide, native grassland mix
2. Dispersal limited	Large, high-severity patch makes dispersal limitation of regeneration likely, but environment is forest-capable.
Quantitative criteria	• Fire severity: high or extra high • Distance to potential seed source: too distant • Future deficit: dry or moist-cold
Potential treatments	• Mechanically treat (dead) if future surface fuel loads are above objective • Plant climate-adapted species
3. Structurally complex	Complex closed canopy forest patch that persisted through fire in a location that is likely climate refugium.
Quantitative criteria	• Tree size: med/large • Canopy cover: closed • Future deficit: moist-cold
Potential treatments	• Create strategic fuel breaks in adjacent locations to limit future fire spread • Variable density thinning to accelerate development of complex structure
4. Stabilizing feedback	Current fire burned through recent treatment (Rx burn, thin, or harvest) or past low/moderate severity wildfire and is likely a stabilizing feedback.
Quantitative criteria	• Fire severity: no change or lower • AND one of: o Time since previous fire: recent AND o Maximum previous severity: lower • OR o Treatment history: treated
Potential treatments	• Use as anchor or core area for other treatments to promote open forest types • Future maintenance burns with managed wildfire or Rx fire
5. Composition mismatch	Tree species composition is not fire-tolerant or does not match site.
Quantitative criteria	Fire resistance score: • Not resistant or moderately resistant for dry forest • Not resistant for moist/cold forest
Potential treatments	• Prescribed fire with or without mechanical treatment • Green tree thinning and/or "salvage from below" • Plant climate-adapted species
6. High canopy cover	Post-fire canopy cover or stem density remain too high.
Quantitative criteria	• Canopy cover: closed
Potential treatments	• Prescribed fire with or without mechanical treatment • Green tree thinning and/or "salvage from below"
7. Resilient structure	All other patches: regeneration not limited, not managed for complex structure.
Quantitative criteria	• None
Potential treatments	• Future managed wildfire • Future prescribed fire with or without mechanical treatment

Objective 6: Foster Science-Based Discussion and Decision Making about Post-Fire Management

We achieved this objective through in person and virtual workshops and a webinar event designed and implemented as part of this project, as well as unplanned (at the proposal stage) invited presentations and subsequent discussion with managers (e.g., Kootenai National Forest leadership team, Trout Creek, MT, July 25, 2018) and collaborative stakeholder audiences (e.g., Resilient Landscapes, Thriving Communities: Achieving a Collaborative Vision of the Future, March 20-21, 2018, Coeur d'Alene, ID) during the project. The efficacy and impact of our planned workshop and webinar events were enhanced by professional facilitation (Lead Facilitator: Jenna Knobloch, Sustainable Northwest) and support from two units in the JFSP Fire Science Exchange Network: the Northern Rockies Fire Science Network and the Northwest Fire Science Consortium.

Assessing the Work of Wildfires. March 27, 2019. Wilbur, Washington, USA.

This event brought together nearly 40 natural resource managers, stakeholders, and scientists, in addition to the research team and two professional meeting facilitators for a day of presentations and scenario planning focused on post-fire landscape assessment and management. The morning session was devoted to conference-style presentation of preliminary results from project team members; the working lunch and afternoon session were devoted to small group activities organized around post-fire landscape evaluations of a recently burned watershed. Small groups were designed to simulate an Interdisciplinary Team and each small group included a project team member in a facilitator/note-taker role. The afternoon session was devoted to facilitated reporting by the small groups and shared identification of priorities for future research (Fig. 22). The small group exercises and facilitated report out and discussion helped the project team identify needs, barriers to adoption, and priorities for future work. Workshop agenda and presentation details are provided in Appendix B.

Figure 22. Facilitated group reporting and discussion at the end of the workshop in Wilbur, WA, March 27, 2019.

Assessing the Work of Wildfire and Identifying Post-Fire Management Needs: Webinar and Linked Virtual Workshop, October 22 & 30, 2020

For outreach that was tailored to virtual requirements of the COVID-19 pandemic, the team planned a webinar presenting the results with a follow up Zoom workshop session with targeted invitees who live in the regions where the data was collected. These virtual format science communication activities replaced planned field presentations and in person workshops due to COVID-19. The objective was to engage land managers to share research results and discuss a framework translating those results into treatment decisions. The webinar and workshop were developed and hosted collaboratively by the research team, along with Sustainable Northwest, and two JFSP Fire Science Exchanges: Northern Rockies Fire Science Network and Northwest Fire Science Consortium. The webinar (Fig. 23) presented research highlights from across the team with an opportunity for a Q&A. There was tremendous interest in the webinar, with 240 registrants, 155 attendees during the event, and 167 additional views of the [webinar recording](#) as of December 30, 2020.

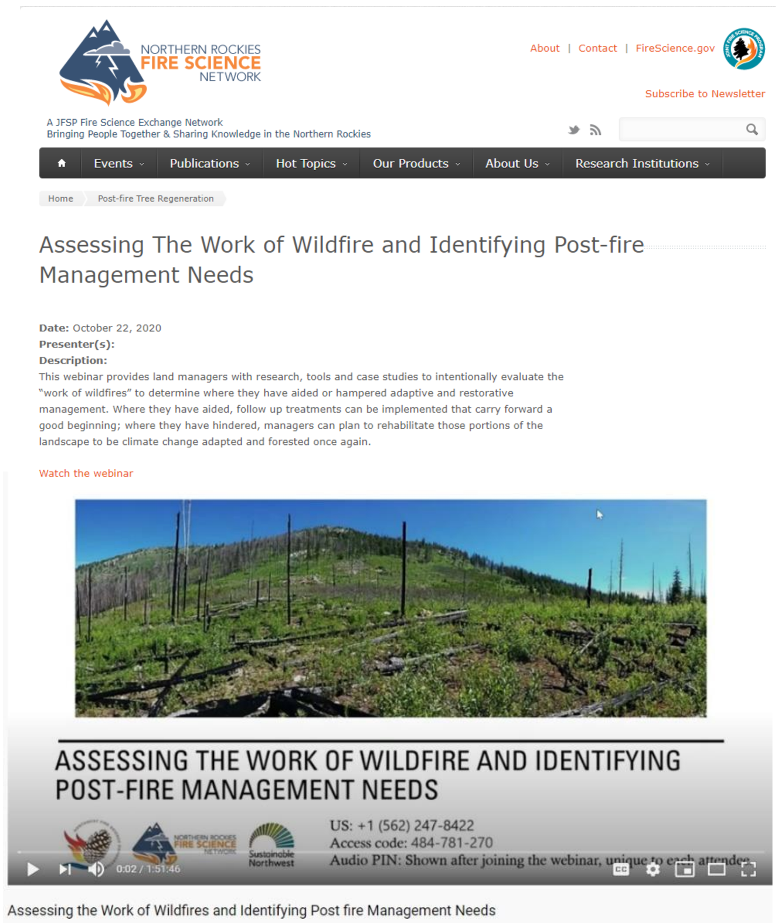

Figure 23. Archived webinar on the NRFSN website.

The team held a virtual workshop via Zoom video conference on October 30, 2020, inviting key forest collaborative members and land managers and from the Colville National Forest and the Okanagan Wenatchee National Forest who had attended the webinar. While attendance was small due to conflicts with other meetings that week, those who attended where central figures in the network, and included representation of both USFS staff specialists and line officers. The workshop session was productive, made more so by professional facilitation provided by Sustainable Northwest, and resulted in a body of co-produced knowledge, ideas, and plans designed to prepare for efficient, science-based post-fire management in the 2021 fire season and future years (Table 5).

Table 5. Knowledge, plans, and ideas co-produced by collaborative stakeholders, USFS agency staff and line officers, and the project team during the October 30, 2020 virtual workshop.

<table>
<tr><td>Before the fire</td><td>

Colville National Forest and other partners in the state using the Potential Operational Delineations (PODs) framework.
There is a need to understand reference conditions:
Stand & Landscape Scale.
% openings that would be non-forest.
The Tapash Sustainable Forest Collaborative is just starting this conversation with the Kittitas Fire Adapted Communities Coalition.
Work on community buy-in for Landscape Evaluations
It takes time- treatments planned from 8 years ago are just getting implemented. Integration of treatments within the area.
</td></tr>
<tr><td>During the fire</td><td>

Where can we make a stand?
Look at past treatments and strategic ridgelines. Past fire behavior. Success this summer on the boundary of a project. Depends on values at risk.
Are past burn severity maps considered during suppression actions? So far timing is far enough apart that they are not. Stickpin fire there wasn't a noticeable effect.
Use of Wildland Fire Decision Support System:
We pass that on to the team. Resource Advisors on the fire take an active role during recon during the fire. This sets the stage for the objectives for the Incident. Goes with an "intent" document. Cost estimate also important. WFDSS has past treatment data.
</td></tr>
<tr><td>Post-fire (Year 1)</td><td>
How much of what we planned did fire accomplish?

RAVG data as potential source of fire effects data
How does this change previous forest structure map?
Scale: Local vs large scale perspective? Barrier: WFDDS is not accessible to everyone.

Post-fire Landscape Evaluation as soon as possible. Approach with an all-lands perspective, with individual landowners deciding what to do. How much of plan did the fire accomplish?

Easy to ask this in dry forest fire environments.
Moist and cold forests more difficult to determine.
Heavy departure- mesic.
Still too many trees after the fire, still work needed with species composition.
There are areas with NEPA and that will need NEPA. Post-fire LE could be a tool for new NEPA.
Post-fire principles- High severity + dry forest- you can rapidly deploy.
Big fires- LE can be used to tie together multiple projects coming off one fire.
Stickpin fire: Some disagreement over what happened, re: post-treatment.
How do treatments interact with each other? LE with implemented treatments on it.
Need:
Understanding of landscape needs for moist forests (for example, too many trees per acre)
Economic value of treatments even though a fire moved through them. For example, did a fire do treatments at how much cost per acre?
</td></tr>
<tr><td>Post-fire (long-term)</td><td>

More information about when and where salvage might be appropriate: Reburns in the future (30+ years) is going to drive uncharacteristic severity. Salvage is a tool for addressing this.
Natural regeneration can be beneficial.
Where to plant? Look at past plantations, better soil sites. Past harvest units
Where not to plant: harsh sites and open sites. Do we want to plant where there is going to be future high fuel loads?
</td></tr>
</table>

Departures from Proposed Activities

While we fully met our project objectives and deliverables (Table 6), analysis of long-term post-fire forest structural development (Objective 1) did not proceed as envisioned due to data limitations. At the time of our proposal, the state of Washington was expecting to acquire lidar data over large portions of our study area. Therefore, while we did directly use LiDAR data as response variables in our analyses of post-fire forest structure, we originally expected to have larger footprint of LiDAR that sampled a wider range of post-fire management scenarios. This increased LiDAR footprint was not available within our project period of performance. We addressed this data limitation in two ways. First, we increased our investment in measurements of forest structure in field plots to complement the available LiDAR data. Second, we investigated digital aerial photogrammetry (DAP) data derived from the Hexagon Imagery Program whose images are used to produce the biannual National Agricultural Imagery Program (NAIP) datasets (Strunk et al. 2019). DAP data would have been an alternative source of high-resolution forest structure data over large, continuous areas. But because we learned that reliable change detection with DAP-derived forest structure models requires a high-resolution ground model—derived from LiDAR—we were still limited by the existing footprint of LiDAR, and thus ultimately used the LiDAR for our final analyses.

Our exploratory analysis with DAP was successful in that it demonstrated proof of concept and identified areas for research and development, and we translated this work into two technical presentations at national scientific conferences. We reported on this change in data and analysis in the FY19 annual progress report. Additionally, we evaluated DAP as a source of post-fire current condition data in Objective 5.

We were not able to use LiDAR forest structure data as predictor variables in in the analysis of fire severity (Objective 2) for the same reasons described above. Instead, we incorporated pre-fire forest structure as explanatory variables using GNN data in our fire severity modeling. Additionally, we used a new trait-based community fire resistance score (FRS) that was not available when our proposal was written as a predictor variable in our severity analysis. FRS was developed based on fire resistance and experimentally verified flammability traits of 28 western North American conifer species (Stevens et al. 2020). FRS was the most important biotic explanatory variable in our models and represents an important advance in predictive fire severity modeling because it is trait-based and thus better captures the underlying physiological and ecological mechanisms regulating fire severity.

Final planned in-person workshops and field visits were converted to virtual events due to COVID-19 precautions, with advance notification to and approval from JFSP (E-mail communication from Becky Jenison, May 14, 2020).

Science Delivery Activities

We maintained an active and successful science delivery program during this project. Science delivery methods included traditional scientific publications and presentations, in person and virtual workshops, a very well attended JFSP Fire Science Exchange Network webinar and highly viewed archived recording, and public presentations (Table 6; Appendix B). This diversified science delivery program reached managers, collaborative stakeholders, agency and university scientists, students, journalists, and the public through multiple platforms.

Traditional science delivery activities included 12 contributed or invited oral presentations at regional, national, and international scientific meetings and two invited academic seminars. Other science delivery products include one published peer-reviewed journal article (Povak et al. 2020) and four additional peer-reviewed journal articles currently in preparation. Working titles and author lists for the in-preparation articles are listed in Appendix B. We intend to publish these articles as a collection, reflecting their interdependence, overlapping geographic scope, and shared focus on post-fire forest management. We have identified the journal *Forest Ecology and Management* as our preferred outlet and Editor-in-Chief Dr. Dan Binkley has invited (e-mail communication, December 18, 2020) submission our manuscripts for peer review and publication as a special section titled "Post Fire Forest Management" in a forthcoming issue of *Forest Ecology and Management*. We expect first submission in the first quarter of 2021.

The two new datasets generated in this project constitute another significant science delivery outcome and are already generating external use and development of secondary science delivery products. The tree regeneration portion of our field dataset has been selected for inclusion in a large meta-analysis project to model post-fire tree regeneration across western US forests led by Kim Davis (University of Montana) and Kerry Kemp (The Nature Conservancy). Proposed products from that work include geospatial maps (summer 2021), a peer-reviewed modeling publication (December 2021), and peer-reviewed data publication (2022 TBD).

Table 6. Deliverables identified in the proposal and their current status.

Deliverable Type	**Status as of December 31, 2020**
Consultations with managers and stakeholders	*Completed:* **Four** presentations to land managers and collaborative stakeholder groups.
Workshop with managers and stakeholders	*Completed:* **One** in person workshop with **40** attendees; **one** webinar with **155** attendees plus **167** subsequent recording views.
Scientific/management meetings	*Completed:* **Twelve** technical/scientific presentations given at **six** different scientific/professional meetings; **two** invited academic seminars.
Peer reviewed journal papers	*Completed:* **One** published refereed paper in the journal *Ecosphere*. *In progress:* **Four** manuscripts in preparation.
Agency workshops	*Completed:* **One** virtual workshop. Format changed from in person to virtual due to COVID-19. Participants (**n = 7**) included representation of US Forest Service staff specialists and line officers.
Final report and data archive	*Completed:* **Final Report** submitted to JFSP; **two** data/metadata submissions to USFS Research Data Archive.

Conclusions

We achieved our overarching goals for this study, which were to investigate drivers of fire-severity and post-fire vegetation development, with an emphasis on how pre- and post-fire management and prior disturbance history modulate these responses, and to evaluate the degree to which fire reduced landscape departure and made progress towards fire-prone forest restoration targets.

Key findings include:

- Abundant post-fire tree regeneration one to three decades after fire, with little evidence of recruitment failure (Fig. 3).
- An influence of both average climate and post-fire weather, with higher seedling densities in cooler and moister climate and weather conditions (Fig. 4). This weather and climate signal portends potential recruitment limitation in future fires that occur in a warmer and drier conditions.
- Converging forest structure in paired treated and untreated (with post-fire management) sites one to three decades after fire. Post-fire harvest has a simplifying effect on residual structure relative to controls, but the effect of fire severity is stronger than that of post-fire treatments (Figs. 6 and 7).
- Evidence that post-wildfire prescribed fire applied in areas the burned at lower severity can further decouple surface and canopy fuels, promoting fire-resistant open canopy structure (Figs. 6 and 7).
- Compelling evidence that recent prior vegetation management, and especially prior prescribed fire and wildfire, moderate fire severity and reestablish stabilizing fire-vegetation feedbacks (Figs. 10 and 11).
- Contrasting outcomes within large, unplanned wildfires (Figs. 15 to 20). In some areas, fires make progress towards restoration or climate adaption goals, improving alignment of the forest structural mosaic with HRV-FRV envelopes and reestablishing stabilizing fire-vegetation feedbacks (Fig. 21). However, unplanned wildfires sometimes increase departures from HRV-FRV benchmarks, for example when extreme fire behavior creates vast open patches and tips forested patches into climate or dispersal-limited non-forest.
- Strong demand from the management, stakeholder, and scientific communities for practical applied science to guide post-fire management and climate change adaptation (Figs. 22 and 23). Recently burned landscapes are the frontline of forest ecosystem change in response to increased fire activity and climate warming, and future applied research beyond the recent focus of post-fire tree recruitment is needed.

Implications for management

Key implications for management are embodied in our post-fire management principles and associated analytical workflow (Table 4) and illustrated with our example landscape prescriptions (Fig. 21). An important theme in the interpretation and application of our results to post-fire management is a shift away from focus on primarily intensive economic salvage in areas that burned with high severity, towards post-fire harvest using a combination of green tree thinning, “salvage from below” and post-fire prescribed fire in areas that burned with low to moderate severity. This represents a shift from primarily focusing on post-fire harvest treatments that mitigate economic effects of wildfires (Nemens et al. 2019) to a management perspective that emphasizes strengthening the beneficial work of fire while considering overall landscape pattern.

Another key implication for management is the important role of prior vegetation management, especially treatments that include prescribed fire, in moderating fire effects and enabling unplanned wildfires to burn in a way that reestablishes stabilizing fire-vegetation feedbacks. Thus, we see a compelling need to increase the pace and scale of restoration treatments in fire-excluded landscapes so that more areas are set to receive wildfire with effects that strengthen stabilizing feedbacks and landscape resilience (North et al. 2012).

Future research

Applied research focused on developing and deploying technology to acquire and process geospatial data characterizing post-fire conditions is an important area for future work. Methods to rapidly update vegetation data layers after a fire occurs (Table 3) will enable land managers to apply the post-fire landscape prescription approach we illustrate (Table 4) in a way that is robust, transparent, and timely. Managers need to be able to rapidly acquire wall-to-wall post-fire data so that post-fire treatments can be accomplished in tight windows: for example, while fire-killed trees still have economic value and before competing vegetation becomes a challenge to reforestation.

We see a need for modern basic and applied research on a wider range of post-fire treatment types and intensities, including long-term responses to post-fire management. Most of the available literature is focused on either intensive economic salvage harvesting in high-severity patches (Nemens et al. 2019), or to a lesser degree, salvage treatments with a fuel reduction focus, also implemented in high severity areas (Johnson et al. 2020). Because of the long legacy of conflict and polarization around post-fire salvage logging (Powell 2019), any sort of post-fire treatment is likely to be controversial. A modern interdisciplinary research program that conders a wider range of post-fire treatments beyond economic salvage and fuel reduction treatments in areas that burned with high severity will help fill this gap in the literature and enable science-based decision making about post-fire landscape management.

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Appendix B**: **List of Completed/Planned Scientific/Technical Publications/Science Delivery Products:

1. Articles in peer-reviewed journals

Povak, N.A., Churchill, D.J., Cansler, C.A., Hessburg, P.F., Kane, V.R., Kane, J.T., Lutz, J.A., Larson, A.J., 2020. Wildfire severity and postfire salvage harvest effects on long-term forest regeneration. *Ecosphere*, *11*(8), p.e03199.

Cansler, C. A., Kane, V. R., Bartl-Geller, B. N., Povak, N. A., Kane, J. T., Churchill, D. J., Hessburg, P. F., Lutz, J. A., Larson, A.J. *In preparation*. Converging forest structure with and without salvage harvest 12-32 years after fire. Target outlet: *Forest Ecology and Management*

Cansler, C. A., Kane, V. R., Kane, J. T., Churchill, D. J., Hessburg, P. F., Lutz, J. A., Povak, N. A., Larson, A. J. *In preparation.* Fire history modulates burn severity in reburns, while daily fire weather and annual climate anomalies influence fire severity in all fires. Target outlet: *Forest Ecology and Management*

Churchill, D.J., Jeronimo, S.M.A., Hessburg, P. F., LeFevre, M., Begley, J., Gray, R., Cansler, C. A., Povak, N. A., Kane, V.R., Lutz, J. A., Larson, A. J. *In preparation.* Are wildfires restoring landscapes? Post-fire landscape evaluations in Eastern Washington, USA. Target outlet: *Forest Ecology and Management*

Larson, Andrew J., Churchill, Derek. J., Jeronimo, Sean M. A., Cansler, C. Alina, Povak, Nicholas A., Kane, Van R., Lutz, James A., Hessburg, Paul. F. *In preparation.* Applying Ecological Principles to Post-Fire Forest Landscape Management. Target outlet: *Forest Ecology and Management*

2. Technical reports
None.

3. Text books or book chapters
None.

4. Graduate thesis
None.

5. Conference or symposium proceedings scientifically recognized and referenced
None.

6. Conference or symposium abstracts

Larson, A.J. Seven principles for restoring fire-prone landscapes in the Inland Northwest.

Resilient Landscapes, Thriving Communities: Achieving a Collaborative Vision of the Future. March 20-21, 2018. Coeur d'Alene, Idaho, USA.

Povak, N., D. Churchill, C.A. Cansler, V. Kane, P. Hessburg, J. Kane, J. Lutz, and A.J. Larson. Influence of wildfire severity and post-fire timber salvage on forest regeneration in mixed-conifer forests. The Fire Continuum Conference. May 21-24, 2018. Missoula, Montana, USA.

LeFevre, M., D. Churchill, S. Jeronimo, P. Hessburg, C.A. Cansler, V. Kane, J. Lutz, and A.J. Larson. Assessing the Work of Wildfires with Post-Fire Landscape Evaluations. The Fire Continuum Conference. May 21-24, 2018. Missoula, Montana, USA.

Kane, J., N. Povak, V. Kane, C.A. Cansler, J. Lutz, D. Churchill, P. Hessburg, and A.J. Larson. Modeling Fire Severity in Eastern Washington Using Mapped Surfaces of Climate, Weather, and Topography. The Fire Continuum Conference. May 21-24, 2018. Missoula, Montana, USA.

Hessburg PF. 2018. Topics in Landscape, Fire Ecology, & Climate Change Research, Development, & Applications. Presented at the plenary session: Postfire Activities and Fire Ecology, The Fire Continuum Conference, Preparing for the future of wildland fire, May 21-24, 2018, Missoula, MT.

Kane, V.R., et al. Are wildfires recreating fire resilient forest structures at landscape-scales in northeastern Washington state? International Association for Landscape Ecology Annual Conference. April 7-11, 2019. Ft. Collins, Colorado, USA.

Churchill, D.J., et al. Integrating the work of wildfires into landscape restoration: Post-fire landscape evaluations. 12th North American Forest Ecology Workshop. June 23-27, 2019. Flagstaff, Arizona, USA.

Kane, V.R., et al. An evaluation of landscape-scale fire-induced change in Washington State, USA. 12th North American Forest Ecology Workshop. June 23-27, 2019. Flagstaff, Arizona, USA.

Larson, A.J. et al. Do wildfires follow fire-prone forest restoration principles? 12th North American Forest Ecology Workshop. June 23-27, 2019. Flagstaff, Arizona, USA.

Kane, J., C.A. Cansler, V. Kane, N. Povak, D. Churchill, J. Lutz, P. Hessburg, A. Larson, L.M. Moskal. 2019. Relative importance of drivers of burn severity in eastern Washington. Presented at the 8th International Fire Ecology and Management Conference—Cultivating Pyrodiversity, Loews Ventana, Tucson, AZ, November 18-22, 2019.

Churchill D, Larson A, Hessburg PF, Povak NA, Kane V, Kane J, Cansler A, Lutz J, Jeronimo S, LeFevre M. 2019 Integrating the work of wildfires into landscape restoration: Post-fire landscape evaluations. Presented in the symposium: Historical and Contemporary Pyrodiversity in Fire-Prone Forest Ecosystems: Relevance to Future Climate and Wildfire Adaptation, at the 8th International Fire Ecology and Management Conference—Cultivating Pyrodiversity, Loews Ventana, Tucson, AZ, November 18-22, 2019.

Kane, V. C.A. Cansler, J.T. Kane, B. Bartl-Geller, N.A. Povak, J.A. Lutz, D. Churchill, P.F. Hessburg, A.J. Larson. 2020. Burn severity, repeat fires, and forest management interact to influence forest structure in northeastern Washington, USA. Ecological Society of America 2020 Virtual Meeting. August 3-6, 2020. Online.

7. Posters

None.

8. Workshop materials and outcome reports

Assessing the Work of Wildfires. March 27, 2019. Wilbur, Washington, USA.

This event brought together nearly 40 natural resource managers, stakeholders, and scientists, plus the research team and two professional meeting facilitators for a day of presentations and scenario planning focused on post-fire landscape assessment and management.

The small group exercises and facilitated report out and discussion helped the project team identify needs, barriers to adoption, and priorities for future work.

NEWFIRE Workshop: Assessing the Work of Wildfires
March 27, 2019
Wilbur Community Center, 1-99 SW Railroad Ave, Wilbur, WA

AGENDA

Time	**Topic or activity**	**Presenter or facilitator**
9:30-9:50	Welcome and introductions	Andrew Larson and Jenna Knobloch
9:50-10:15	Keynote: Motivating needs and context of NEWFIRE	Paul Hessburg
10:15-10:40	Post-fire landscape assessments: the work of wildfire	Derek Churchill
10:40-11:05	Post-fire tree regeneration and climate	Nick Povak & Dan Donato
11:05-11:15	Break	
11:15-11:40	Post-fire fuel dynamics and fuel treatments	Andrew Larson & Dave Peterson
11:40-12:00	Introduction to workshop activity and assignment	Derek Churchill & Erin Peterson
12:00-1:30	Working lunch and small group workshop activity	Assigned groups
1:45-3:30	Facilitated report out by assigned groups, discussion and synthesis	Jenna Knobloch, All

Fall 2020 Webinar and Linked Virtual Workshop

For outreach that was tailored to virtual requirements of the pandemic, the team planned a webinar presenting the NEWFire results with a follow up Zoom workshop session with targeted invitees who live in the NE Washington region where the data was collected. These virtual format science communication activities replaced planned field presentations and in person workshops due to COVID-19. The objective was to engage land managers to share research results and discuss a framework translating those results into treatment decisions. *The webinar and workshop were developed and hosted collaboratively by the research team, along with Sustainable Northwest, the Northern Rockies Fire Science Network, and the Northwest Fire Science Consortium.*

Webinar: Assessing the Work of Wildfires and Identifying Post-fire Management Needs
2 hours, October 21, 2020.

Recording here

The webinar presented research highlights from across the NEWFire team with an opportunity for a Q&A. There was tremendous interest, with 240 registrants, 155 attendees during the live event, and 167 additional views of the webinar recording to date. While most of the participants were from the Pacific Northwest, there were many attendees from across the western US and western Canada, and additional international participation (Chile and Croatia). The post-webinar survey indicated that overall, it was very successful. Of those that filled out the survey (n=67), 65% agreed with the statement “I will apply information from this webinar to my work immediately” and 93% agreed with the statement “Concepts presented in this webinar are applicable to me and my work.”

Webinar presentations:

Hessburg PF. 2020. An ecological foundation for understanding the “work” of modern wildfires. Presented at the Joint Fire Sciences-Sustainable Northwest-NW Fire Science Consortium Webinar, October 21st, 2020.

Povak NA, Churchill DJ, Cansler CA, Hessburg PF, Kane VR, Kane JT, Lutz JA, and Larson AJ. 2020. Wildfire severity and postfire salvage harvest effects on long-term forest regeneration. Presented at the Joint Fire Sciences-Sustainable Northwest-NW Fire Science Consortium Webinar, October 21st, 2020.

Cansler CA, Kane VR, Kane JT, Lutz JA, Churchill DJ, Larson AJ, Hessburg PF, Povak NA. 2020. Fire severity & forest structure in northeastern Washington: First fires, reburns, and pre-fire and post-fire treatments. Presented at the Joint Fire Sciences-Sustainable Northwest-NW Fire Science Consortium Webinar, October 21st, 2020.

Churchill DJ, Cansler CA, Hessburg PF, Povak NA, Kane VR, Kane JT, Lutz JA, and Larson AJ. 2020. Developing post-fire prescriptions for burned eastern Washington landscapes. Presented at the Joint Fire Sciences-Sustainable Northwest-NW Fire Science Consortium Webinar, October 21st, 2020.

Northeast and Central Washington Virtual Workshop
The team held a zoom meeting following the webinar, inviting key land managers and forest collaborative members from the Colville National Forest and the Okanagan Wenatchee National Forest who had attended the webinar. While attendance was small due to conflicts with other meetings that week (7 participants not including members of the project team or facilitator), those who attended where central figures in the network (for example, James Pass, the lead Silviculturist for the Colville National Forest).

Lessons Learned and Next Steps:
Participants were familiar with the PODs framework, as it is being rolled out across the Pacific Northwest by the Forest Service, which color codes areas (green, yellow, red) based on risk. The conversation often blended findings from this project with concepts out of the PODs framework. Similarly, relating this project to the Wildfire Decision Support System (WFDDS) came up frequently. Future communications might frame how this project complements, contrasts, or overlaps with other frameworks and decision support systems. An additional identified need was a "principles" type review and synthesis paper to help land managers distill and apply the key science concepts developed during this project to post-fire land management.

9. Field demonstration/tour summaries
None. Field tours during the final year of the project were planned in the original proposal but were reconfigured as virtual events due to COVID-19.

10. Website development
None.

11. Presentations/webinars/other outreach/science delivery materials

Larson, A.J. Fire ecology and forest management. The Future of Wildfire – A Workshop for Journalists. April 19-21, 2018. Institute for Journalism and Natural Resources. Missoula, Montana, USA.

Larson, A.J. Fire-prone landscape restoration. Presentation to the Kootenai National Forest Leadership Team. July 25, 2018. Trout Creek, Montana, USA.

Churchill, D.J. and A. J. Larson. Webinar/conference call presentation to the Washington Forest Collaborative Network. Jan 16, 2019. N = 21 participants from collaboratives, NGOs, state/local agencies. No federal land managers participated in this webinar as occurred during the January 2019 government shutdown. Online.

Larson, A.J. Fire ecology and forest management. The Future of Wildfire – A Workshop for Journalists. April 5, 2019. Institute for Journalism and Natural Resources. Missoula, Montana, USA

Churchill, D., A.J. Larson, P.F. Hessburg, V.R. Kane, N.A. Povak, C.A. Cansler, J.A. Lutz. 2019. Learning to Live with Fire in Central & Eastern Washington? Washington Association of Conservation Districts Annual Meeting, 12/04/2019. Tacoma, WA, USA.

Larson, A.J. Integrating the Work of Wildfire into Landscape Restoration. Forest, Rangeland, and Fire Sciences Seminar. University of Idaho College of Natural Resources Moscow, Idaho, USA. March 4, 2020. Moscow, Idaho, USA.

Cansler, C.A. Using multi-scale data sources to examine the work of wildfires in Northeastern Washington State, USA: Implications for post-fire management. School of Environmental Studies departmental seminar (ES503/603) at the University of Victoria (British Columbia). 12/2/2020. Online.

Appendix C: Metadata

Dataset 1. Submitted to USFS Research Data Archive

Povak, Nick A. Churchill, Derek J., Cansler, C. Alina, Hessburg, Paul F., Kane, Van R., Kane, Jonathan T., Lutz, James A. and Larson, Andrew J. Wildfire severity and postfire salvage harvest effects on long-term forest regeneration. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2020-0079.

Description. Field dataset composed of measurements of post-fire forest structure and tree regeneration at sites with and without salvage logging.

Dataset 2. Submitted to USFS Research Data Archive

Churchill, Derek J.; Jeronimo, Sean A.; LeFevre, Miles; Begley, James; Gray, Bob; Cansler, C. Alina; Hessburg, Paul F.; Povak, Nick A.; Kane, Van R.; Kane, Jonathan T.; Lutz, James A.; Larson, Andrew J. 2020. Pre and post fire forest structure and composition photo-interpreted data for four sub-watersheds in Eastern Washington, USA. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2020-0084

Description. Geospatial data characterizing pre- and post-fire forest structure and composition based on aerial photo interpretation.